Chapter 7

Seasonal snow cover, ice and permafrost

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1 Introduction

This report examines the impact of climate change on the terrestrial component of the cryosphere including seasonal snow cover, mountain glaciers, ice sheets, frozen ground including permafrost (ground that remains frozen for more than one year) and seasonally frozen ground. Potential changes in these elements of the terrestrial cryosphere as a result of the projected changes in climate induced by enhanced atmospheric concentrations of greenhouse gases (GHG) are discussed. In addition, this report reviews the current understanding of the likely ecological and socioeconomic consequences of these changes.

The changes in climate that form the foundation of this chapter are primarily based on the scenario developed at the Villach 1987 meeting. Illustrative examples, however, will also make use of scenarios developed using palaeo-based reconstruction techniques and those produced by various computer simulations using general circulation models (GCM) depending on the specific scenario used by the referenced authors.

Currently, most of the land-based mass of ice is contained in the ice sheets of Antarctica and Greenland (Table 7.1). Compared to the total volume of the oceans, the ice volume stored in Greenland and Antarctica is relatively small at 2.1% (Oerlemans and van der Veen, 1984).

The largest areal extent of the snow is observed during the winter when seasonal snow cover occurs. The maximum extent of this snow cover can be as much as 62% of the Eurasian continent and virtually all of North America north of 35° during some portion of the winter season. The fact that seasonal snow in temperate latitudes is typically close to its melting point suggests that a temperature increase of even a few degrees could have a dramatic influence on its presence and its characteristics.

Seasonal snow cover, ice and permafrost will be significantly affected by the suggested GHG-induced climatic changes. The projected climate warming and changes in precipitation will, in general, decrease the global areal extent and masses of the seasonal snow cover, ice and permafrost. For most locations which currently experience a seasonal snow cover and seasonally frozen ground, the projected climate changes suggest a decreased duration of snow cover and increased length of the frost-frec season and, in some cases, a complete withdrawal of snow. In the case of glaciers and ice sheets the impacts of the projected changes in climate are complicated by the complex relationships between the dynamics of these ice masses and projected increases in temperatures and changes in precipitation characteristics. Although the relationships between permafrost and climate are complex, the projected climatic changes will most likely lead to increased degradation. The associated changes in seasonal snow cover, ice and permafrost have ramifications in terms of both local and global hydrology (eg meltwater flow, peak discharge, seasonal distribution of runoff and sea-level rise), nature and distribution of vegetation, as well as local and regional terrain stability (eg subsidence, landslides and other mass movements).

Changes in seasonal snow cover, ice and permafrost can also affect climate through various feedback mechanisms. Snow and ice surfaces have much higher albedos than do other natural land surfaces and, therefore, are capable of reflecting a greater percentage of the incident solar radiation. Decreasing coverage of snow and ice will, therefore, lead to an increase in the amount of solar radiation absorbed by the earth, thereby enhancing the global warming process. This may be further enhanced if increased cloudiness accompanies increased warming (see Working Group I Report). The additional long-wave radiation from the new snow-free land would be 'trapped' even more than at present if cloudiness also increases. Furthermore, degradation of permafrost could alter atmosphere-biosphere fluxes of GHG (eg methane), thereby influencing the amount and rate of global warming. Increased rates of melting, however, will reduce the potential climatic warming as energy is used to melt the ice.

Another factor that should not be neglected in this assessment is the influence of human activities on seasonal snow cover, ice and permafrost. The influence is felt mainly locally through anthropogenic changes in the surface and quantity and quality of the snow or ice. These changes disrupt the surface (change in albedo, exposure of ice mass etc) and thereby alter the ablation and degradation processes. Examples of these disturbances are abundant, ranging from the impact of building snow roads and ice bridges, and of traffic on glaciers and ice sheets, to surface disruptions during the building of structures and pipelines. In the case of snow, human activities such as building of structures and certain

Table 7.1 Relative extent of terrestrial areas of seasonal snow cover, ice and permafrost (after Washburn, 1980a and Rott, 1983).

	Area (million km^2)	Volume (million km^3)
Land ice		
Antarctica	13.9	30.1
Greenland	1.8	2.7
Small ice caps	0.35	0.2
Mountain glaciers	0.2	0.03
Major permafrost region		**Percentage underlain by permafrost**
USSR	16.84	50
Canada	9.38	50
China	9.38	22
Greenland	2.18	100
USA (Alaska)	1.52	82
World land area	140.7	20-25
Northern hemisphere	7.6*	
Continuous	17.3*	
Discontinuous	2.33*	
Alpine permafrost		
Land ice and seasonal snow	**Area**	**Volume**
Northern hemisphere		
Early February	46.3	0.002
Late August	8.7	
Southern hemipshere		
Late July	0.85	
Early May	0.07	

* Approximate

types of logging practices can actually increase the amount and duration of snow cover and, thereby, also influence any underlying permafrost.

The relationships between the dynamics of climate and seasonal snow cover, ice and permafrost are exceedingly complex and, because of their nature (eg remote, massive, dynamic etc), difficult to study. Observation techniques and analysis methodologies that will provide a better understanding of the dynamics of these relationships are relatively new or under development and therefore have not been widely used.

Limited research and basic data combined with the lack of involvement of representatives from social and economic communities in programs which examine the implications of the suggested changes lead to conclusions which are in most cases highly speculative. This does not diminish in any way the need for effective and timely responses. With climatic changes, seasonal snow cover, ice and permafrost will be affected and the suggested changes are qualitatively plausible. Actions to solve problems cannot be made until the causes of the problems are more than speculative. This alone suggests that decisive actions are required to obtain more comprehensive information and to undertake directed, integrated research. Long-term research should be designed to better define the dynamics of seasonal snow cover, ice and permafrost and the bounds of possible response strategies.

2 Environmental impacts

2.1 Seasonal snow cover

Seasonal snow cover is for the most part a transient element of the earth's surface persisting at one location anywhere from a few days to a major portion of the year. The areal extent of seasonal snow cover is also highly variable (Fohn, 1989) changing continually during a particular season and from one year to the next. These temporal and spatial fluctuations are in response to the variable microclimates and terrains typical of those areas which experience seasonal snow cover.

The impacts that GHG-induced climatic changes would have on seasonal snow cover, particularly at higher latitudes, are not known with certainty. In those areas where spring temperatures are expected to increase with early spring snowfalls becoming rain events and, where warm air advection events could become more frequent, the duration of snow cover will decrease. In those areas where temperatures are projected to remain below or at freezing and where winters are expected to be warmer but wetter, the snow pack will increase and hence take longer to melt in the spring. Increased snowfall and suggested changes in the snow cover dissipation could have serious repercussions by delaying planting and access to pastures and rangelands.

Computer-generated climate scenarios provide some indications of possible impacts of GHG-induced climate changes on seasonal snow cover at a continental scale (Schlesinger, 1986). When interpreting these results it should be noted that current versions of these models have rudimentary simulations of the exchanges between the ocean and the atmosphere including the impact of sea ice and, because of their spatial resolution, limited representation of potential regional impacts and elevation differences. As would be expected under the influence of global warming, the simulations indicate that the area covered by snow will decrease in both the southern and northern hemispheres. In terms of the mass of snow, however, the responses are less uniform. In general, within the Northern Hemisphere, a decrease in the mass of snow is indicated, whereas an increase occurs within the Southern Hemisphere. These changes in mass, however, are not uniform but, to some degree, depend on latitude, elevation and season. Throughout the year, snow mass north of 30°N latitude and north of 68°S latitude is expected to decrease in response to climatic changes, while snow mass is expected to increase over Antarctica, south of 68°S latitude.

As depicted by computer simulation (note limited modelling of orographic features in GCM), changes in snow mass during the winter within the Northern Hemisphere do not appear to be related to elevation; however, during the summer, elevations below 1500 m predominantly have snow mass decreases, while locations at higher elevations show both increases and decreases. The increases in Northern Hemisphere snow mass occur over the Greenland interior in both summer and winter. In the Southern Hemisphere, snow mass increases are suggested during summer and winter in the interior of Antarctica above the 400 m level with decreases around the Antarctic coastline.

The suggestion that snowfall along the coastline of Antarctica will decrease as a result of projected climatic changes is debatable. Projected reductions in the sea ice cover around the Antarctic continent as a result of climatic changes will increase the area of open water, thereby providing an additional moisture source for increasing atmospheric moisture and, thus snowfall on the adjacent land or ice sheet.

Possible impacts of GHG-induced climatic changes on seasonal snow storage and the snowline have been estimated for New Zealand (Fitzharris, 1989) using a snow wedge simulation model with temperature increased by 3°C and precipitation by 15% above current levels. When applied to the South Island, this model suggests that the snowline will rise 300-400 m, with a decrease in snow accumulation below 2300 m. Seasonal snow storage, which now averages 350 mm, will decrease to 190 mm, and the area covered by winter snow will be halved.

Within the Alps, Kuhn (1988) suggests that a permanent snow cover will be observed only at altitudes above 1500 m by the year 2050 as a result of the projected changes in climate. An analysis of the recent seasonal distribution of snow cover at 20 stations in the Alps (Fohn, 1989) found large seasonal fluctuations with no long-term trend. The last five to seven winters did, however, clearly show lower than normal snow depths on 1 January. Despite the fact that these depths were not outside the range of normal fluctuations, continuation and intensification of this trend would have serious ramifications to snow dependent components of the Alps economic communities (eg skiing and tourist industries).

Owing to its high air content, dry snow is a very effective insulator for the ground. Significant decreases in snow cover will result in increased susceptibility of agricultural crops (eg winter wheat), natural ecosystems perennial species (eg trees and shrubs) and animals (eg hibernating species) to adverse effects of cold temperatures and frost where freezing temperatures continue to occur. Lack of sufficient insulation by snow cover has been cited as a factor contributing to reductions in forest health and losses in overwintering agricultural crops. Lack of insulation from snow cover has also led to damages to urban infrastructure and to other facilities as a result of frost heave.

Climate models have shown that snow cover, through its influence on surface albedo, is a critical factor in the local and global climate system

(Budyko 1969; Manabe and Wetherald, 1980), particularly at high latitudes/altitudes where the ground may be covered with snow from 6-9 months each year. This albedo-temperature feedback mechanism is related to the fact that snow, depending on its quality, has a very high albedo (0.3-0.9) reflecting the sun's radiation 2-3 times more than grassland and soil. In addition, although snow absorbs and emits long-wave radiation most effectively, the emission is limited by the fact that the snow surface temperature is below 0°C. Based on this limitation, snow cover hampers a fast warming of the adjacent air relative to that which would occur from a warmer, snow-free surface.

Changes in the duration and area covered by snow could, therefore, have significant impact on local, regional and global climates (Fohn, 1989). Where climatic warming leads to decreased snow cover a lowering of the surface albedo will occur. This in turn would result in more absorption of solar energy, and thus increased warming of the adjacent air (positive feedback). In those areas where climatic warming results in increased snow cover, surface albedo would increase which would decrease the solar radiation absorbed by the surface. This would reduce warming of the adjacent air.

Any increase in precipitation should lead to more frequent summer storms and more freezing rain in the autumn. Although the duration of the snow cover season may be shorter, substantial precipitation increases could lead to more snow accumulation. Global warming might advance the melt season so that melt will no longer occur within the intense solar insolation period near the solstice. Snow accumulations, which formerly provided late-season local water sources required to maintain wetlands, may not persist (Woo, 1989).

2.2 Ice sheets and glaciers

The relationships between climatic changes and ice sheet and glacier responses are complex and, because of relatively limited monitoring and research, are not yet fully understood. Projected increases in air temperature, because of its relationship with the surface energy budget, may increase melting rates. However, other factors such as changes in winter precipitation and surface albedo and in the case of ice sheets, iceberg discharge and ocean-ice shelf melting and freezing, add to the complexity of the response.

The bulk of the earth's ice mass is stored within the Antarctic ice sheet (see Table 7.1). The continent, which is approximately 98% ice covered, is naturally divided into two parts: an eastern portion rests on continental crust which, without an ice load would be dominantly above sea-level; and a large western portion which is underlaid both by continental crust and ocean. A review of available evidence from mass balance studies (Budd and Smith, 1985) suggests that the rate of accumulation of ice and the total rate of discharge are nearly in balance for this ice sheet with a discrepancy from 0-20% (due mainly to uncertainties in iceberg discharge, accumulation data, and in the rates of melting below the major ice shelves). The Antarctic ice sheet, however, is probably still adjusting its mass balance to changes that were initiated hundreds or even a few thousand years ago (it is quite probable, dynamically, that it is in fact still responding to the transition out of the last glacial period, over 11,000 years ago).

The Greenland ice sheet is smaller with portions of the continent in the coastal areas permanently ice free. It is not possible at present to estimate reliably the mass balance of the Greenland ice sheet because of a lack of comprehensive observations. Recent estimates (Zwally et al., 1989) using satellite observations, however, indicate that the Greenland ice sheet has thickened by approximately a quarter of a metre a year since the late 1970s. Zwally et al. hypothesise that the observed thickening is a direct measure of the amount of new snow accumulating on the ice sheet.

Characteristics of the Antarctic and Greenland ice sheets are summarised in Table 7.2. Apart from the major ice sheets, small ice caps are found on some Canadian, Norwegian and Soviet islands (eg Ellesmere Island where three ice caps cover an area of more than 20,000 km^2 and Svalbard, where three ice caps cover 15,000 Km^2 of a total 36,000 Km^2).

The effects of GHG-induced climatic changes on ice sheets will be to bring them out of balance (mass balance) and to gradually warm them up (Oerlemans and van der Veen, 1984). Surface melting with runoff to the sea, particularly for Antarctica, is unlikely to be significant during the next century. In the case of the southern portion of the Greenland ice sheet, which has huge ablation zones in the true temperate glacier sense, surface melting with runoff may be significant (possible contribution to sea-level rise in the next hundred years).

The relation between precipitation changes and temperature changes in polar regions is of central importance to understanding current and future behaviour of the ice sheets (Zwally, 1989). In polar regions, enhanced precipitation is associated with warmer temperatures because of the greater moisture capacity of warmer air and the increased

Table 7.2 Characteristics of the Greenland and Antarctic ice sheets (based on Oerlemans and van der Veen, 1984).

	Greenland	**Antarctica**
Area (million km^2)	1.8	13.9
Mean ice thickness (metres)	1530	2160
Ice volume (million km^3)	2.7	30.1
Maximum surface elevation (metres)	3300	4000
Annual accumulation (cm ice depth/year)	34	17
Loss of ice (%)		
Calving	50	99
Melting	50	1

availability of moisture as the ocean area covered by ice declines. Schlesinger and Mitchell (1987) suggest that the increase in precipitation is 5% to 20% per degree Kelvin. Owing to the projected changes in temperature, precipitation and cloudiness and the influence these have on ice sheet accumulation and ablation, the dominant short-term effect of these changes may be growth of both the Greenland and Antarctic ice sheets, but in the case of Greenland may be offset by increases in melting in marginal areas.

The warming of the ocean as a result of climatic changes may have an important impact, particularly on the west Antarctic ice sheet. For a significant impact, however, the increased temperatures must reach the deeper layers of the ice sheet, a process which could take several thousand years.

Using a scenario based on palaeo-based reconstructions, Kotlyakov and Grosswald (1981) suggest that in Greenland the altitude at which the ice sheet will continue to accumulate ice will rise 250-650 m under the impact of projected climatic changes. This level of change could lead to a two-fold growth of the ablation area and an annual lowering of the Greenland ice sheet at an average rate of 0.5-0.7 m/year. Other calculations for the Greenland ice sheet (Ambach, 1980) indicate that as a result of a 3°C increase in surface air temperature and a 12% increase in precipitation, a substantial decrease in its mass balance may result in a decrease of 3% in ice volume over the next 250 years (which could contribute to a rise in sea-level of approximately 0.2 m). Braithwaite and Olesen (1984) have shown that temperature and ablation of Greenland ice are related. They hypothesise that a 3°C temperature increase from 2°C to 5°C would result in a 100% increase in the melt rate (from 20 $kg/m^2/day$ to 40 $kg/m^2/day$). The role of sensible heat flux is considered to be of paramount importance in determining the state of balance of the Greenland ice sheet (as well as other ice sheets), however, this effect is still not well understood.

Projected changes for the Antarctic ice sheet are complex. A preliminary assessment that assumes an increase in surface air temperature of 3°C and a 12% increase in precipitation during the next 100 years suggests an increase of the Antarctic ice volume of approximately 0.5% after 250 years (which could contribute to a decrease in sea-level of approximately 0.3 m). Kotlyakov and Grosswald (1981) hypothesise that the eastern Antarctic ice sheet may remain unchanged as a result of the projected climatic changes.

In contrast the western Antarctic ice sheet like other marine ice sheets, is inherently unstable and could be affected by ground-line retreat and by the rapid dispersal of ice into the surrounding oceans by way of relatively fast-flowing ice streams (Bindschadler, 1990). Rapid changes recently observed on the west Antarctic ice sheet indicate possible instability. These observations, combined with the potential socioeconomic consequences should such a collapse occur (an immediate surge in global sea-level of up to 6 m), however, suggest that the west Antarctic ice sheet should continue to be closely studied.

Climate does influence the dynamics of glaciers and small ice caps through its impact on the amount of snow that collects on their surfaces and the amount of snow and ice lost by melting (Paterson, 1981; Oerlemans and van der Veen, 1984). The response of a particular glacier or ice cap to climate, however, is complicated owing to the large number of other factors (eg glacier geometry, debris cover, ice thickness-mass balance feedback, and calving).

The annual mass balance of a glacier is defined as the difference in water equivalent between accumulation and ablation at the surface, summed over the area of the glacier. Accumulation normally is a result of snow which is transformed into ice; however, avalanches, rime formation and freezing of rain within the snowpack also add mass. Melting followed by runoff, evaporation, removal of snow by wind, sublimation and calving of icebergs are primary ablation processes. All of these accumulation and ablation processes will be affected by climatic changes with resulting impacts on glacial and ice cap masses.

Glacier mass balance, although complicated by background 'noise' inherent in glacier dynamics due to local effects, is considered sensitive to climate (temperature, precipitation, cloudiness etc) and thus is an effective indicator of climatic change. The Permanent Service for the Fluctuation of Glaciers (now the World Glacier Monitoring Service) has been archiving mass balance data for approximately 100 glaciers. Examination of the trends of mass balance data for five glaciers with relatively long records (since 1946) indicates decreasing values over the last few decades. Shrinkage has been most pronounced at mid-temperate latitudes (eg 0.37 m/year from 1934 to 1982 at Hintereisferner in the Austrian Alps) and relatively minor at higher latitudes (eg 0.06 m/year in the Canadian Arctic and 0.25 m/yr in Scandinavia (Norway)).

Projected increases in precipitation may cause some glaciers to advance despite increased ablation. This may presently be reflected by the increase in mass balance of certain Canadian and US glaciers, particularly those dominated by the effects of winter snowfall (eg Blue Glacier in northwest US and Sentinel Glacier in southwest Canada).

Most Andean glaciers have receded dramatically from their positions in the mid-late 19th century (Clapperton and Sugden, 1988) with the period of most rapid recession being between the early 1930s and the early 1960s. Colombian glaciers have decreased in extent by one-third between 1939 and 1969 (Wood, 1970). The complete disappearance of many small glaciers and perennial snowfields in the Pico Bolivar area of Venezuela has resulted as the snowline has risen approximately 6 m per year in this area during the period 1885-1972 (Shubert, 1972). In New Zealand some glaciers are advancing whereas Heard Island (subantarctic island) glaciers are retreating.

A preliminary assessment based on a climatic change scenario which includes a 1°C increase in temperature and an increase in accumulation of 150 mm/year, suggests that an increase of 190 m could occur for the height above which glaciers may realise a net gain in mass in the European Alps (National Research Council, 1985). The projected increase in height is 230 m when the added accumulation was modelled as occurring in the winter months exclusively.

Following the palaeo-based reconstructions of Budyko et al. (1978), Kotlyakov and Grosswald (1981) conclude that the response of glaciers will depend on their type and geographic location. The net mass balance of mountain glaciers in the Eurasia temperate zone will remain essentially unchanged by the 2020s since increases in ablation will be balanced by suggested increases in snowfall. The ablation on the ice caps in the Soviet Arctic archipelagoes is expected to reach 4-6 m (water equivalent) of which only 10-15% will be balanced by increased accumulation. This would suggest that the archipelagoes, with their mean present-day ice thickness of 150-250 m may become completely free of glaciers within the next several decades.

Kuhn (1989) examined the impact of a particular climate scenario for the year 2050 (including a temperature increase of 3°C) on alpine glaciers in Austria. Based on this analysis, he hypothesised that little or no ice may be found below 2500 m and only slightly more than half of the existing glacier surfaces will remain ice covered. The areas from which glaciers retreat would be converted into morphologically highly unstable moraine slopes and forefields which could contribute to landslides, mudflows and increased sediment loads in rivers. At high elevations and high latitudes summer conditions are such that the surface energy balance does not support releases of significant quantities of meltwater. At lower elevations and latitudes glacier ice is exposed to temperatures sufficient to allow melting for several months of the year and, therefore, significantly impacts local and regional hydrology.

The rate of production of meltwater from glaciers and small ice caps is influenced by the incoming solar radiation and by the albedo of their surfaces. Observed data indicate that warmer than average summers will tend to cause significant increases in runoff. The effects of changes in precipitation on these ice masses, however, are less straightforward. Changes in precipitation will influence ablation and meltwater production from glaciers and ice caps by affecting surface albedo and indirectly by associated changes in cloudiness and their effects on incoming solar radiation. For example, the previously mentioned increase in snow cover and/or longer persistence of the snow cover in the spring could reduce early season melting and meltwater release from these ice masses.

One concern regarding the melting of ice sheets and glaciers is related to the impact of this additional water on sea-level. Little if any sea-level change currently observed is caused by wasting of the Greenland ice sheet (a stable or slightly positive state of mass balance), and the Antarctic ice sheet, as mentioned above, is most likely growing, taking water out of the sea. The glaciers and small ice caps of the world outside of Greenland and

Antarctica, however, have in general been shrinking during the past 100 years (Meier, 1984). Sea-level is currently thought to be rising at a rate of 1 to 3 mm/year (Meier, 1990) although this change is far from uniform throughout the world. The rise in sea-level currently observed could be partly attributed to the wastage of alpine glaciers located in the mountains ranges along the Gulf of Alaska, in Central Asia, and from the Patagonian ice caps. Also contributing to the rise in sea-level are such processes as thermal expansion of sea water or the tectonic effects, isostatic rebound, erosion, and sedimentation. Estimates of the effect of current ice wastage compared with that projected under conditions of doubled $C0_2$ concentrations are shown in Table 7.3.

Evidence of extensive forest cover (dated at 3000 year bp) beneath present-day glaciers in the Rockies and coastal mountains in western North America provides further evidence that within the recent past, vast mid-latitude areas were deglaciated. If such déglaciation occurred today water supplies and local climates could be dramatically changed in these regions.

Changes in the amount of melt occurring and the characteristics of glacier or ice sheet surfaces can affect the local and possibly the global climate (Oerlemans and van der Veen, 1984). Glaciers and ice sheets influence climate through their impacts on the local and global energy balance. Energy is required to melt ice and this energy (radiation, sensible and latent heat) is taken from the surrounding air (directly or indirectly) and water. Increases in the amount of ice experiencing melt could therefore lead to a general cooling of the atmosphere and surrounding waters. This potential cooling will have a greater effect on local climate than global climate as melting 1% of the terrestrial ice in 100 years requires a global average of 0.06 W m^2 which is negligible compared to the CCyinduced heat fluxes.

Another factor to consider regarding the impact of changes in these ice masses on the energy balance is that snow and ice that make up the surfaces of glaciers and ice caps reflect more solar radiation than other natural surfaces (see previous discussion on seasonal snow cover). Decreases in the quantity and quality of the surfaces of these ice masses could enhance the warming effect.

2.3 Permafrost

2.3.1 Nature, extent and stability of permafrost

Permafrost is the term used to describe ground (soil or rock) that remains at or below 0°C throughout the year for at least two consecutive years. Permafrost usually contains ice in various forms, from ice held within soil pores to massive bodies of more or less pure ice many metres thick. The presence of ice in permafrost makes it behave uniquely as an earth material, and also makes it sensitive to climatic warming. Dramatic visual evidence of permafrost terrain such as pingos, patterned ground, earth hummocks, ice wedges, palsas, mass movement and thermokarst features are all dependent to some extent on the presence of ice (and especially phase changes of the ice) in the ground.

Evidence of the existence of permafrost has been dated as far back as 600 million bp (Tarling, 1980). It does appear, however, that permafrost has not persisted throughout geological time, but occurred rather sporadically without a discernible pattern. Most of present permafrost is many thousands of years old and formed during the last glacial period or Pleistocene. Permafrost containing large amounts of ice and vulnerable to thaw is often of more practical significance. Today, permafrost underlies 20-25% of the land surface of the earth (Figure 7.1) in the polar and circumpolar regions, and in alpine areas at lower latitudes. Freezing conditions in the surface layers of the earth (seasonal and perennial) are also found at temperate latitudes, and at high altitude in the tropics. Elsewhere permafrost is found in Antarctica, on high-latitude islands, in the mountain ranges of Scandinavia, Europe, North America, Central Asia, Chile, and South Africa, and scattered low-latitude peaks (eg Fujiyama and Kilimanjaro). In ice-covered regions permafrost occurs at glacier margins and in nonglaciated oases.

Permafrost is also widespread beneath the seabed in the Arctic Ocean (Sellman and Hopkins, 1984). However, because of freezing point depression as a result of the salts present, the occurrence of extensive ice-bonded material is limited to the continental shelf areas which were exposed to sub-areal conditions during the Pleistocene (Hunter, 1988). Such permafrost (submarine permafrost) may be considered as relict (permafrost which formed under past climatic conditions and which could not form under present conditions) and is undergoing degradation (ie thawing). In coastal areas where the sea normally freezes down to the seabed, permafrost is contemporary.

Table 7.3 Effect of terrestrial ice sheets on sea level, adapted from a workshop (National Research Council, 1985) and Meier, 1990.

Ice mass	**Present yearly effect on sea-level (mm/year)**		**Cummulative effect by Year 2100 for 2 x CO_2 atmosphere (metres)**	
	NRC	**Meier**	**NRC**	**Meier**
Glaciers and small ice caps	0.2 to 0.8		0.1 to 0.3 (0.3 to 0.6 for complete melt)	0.02 to 0.3
Greenland ice sheet	-0.5 to +0.3	-0.2 to -0.7	0.1 to 0.3	-0.04 to 0.2
Antarctica	-1.2 to 0.0	-0.5 to -1.0	-0.1 to 1.0 (0.0 to 0.3 most probable)	-0.5 to -0.1
Total	-1.5 to +1.1		0.1 to 1.6 (0.2 to 0.9 most probable)	-0.5 to +0.4

The greatest permafrost thicknesses occur as a result of a combination of low surface temperature, low geothermal heat flow and relatively high thermal conductivity and are also related to the non-glaciated past; permafrost extends to a depth of 1000 m or more in Canada (Judge, 1973), to 1500 m in the USSR (Melnikov, 1978), and 100-200 m in China (Youwu and Zhou, 1983). The development of permafrost to such thicknesses requires the persistence of suitable climatic conditions on a geologic time scale, thus, to some extent, the depth of permafrost is dependent on its age (Kudriavtsev, 1965; Melnikov, 1978; Judge, 1973).

Although permafrost is directly temperature-dependent, its occurrence also depends on a number of local and other climatological factors (Washburn, 1979; Williams and Smith, 1989). The relationships between the different factors and permafrost are schematically represented in Figure 7.2 (Nieuwenhuijzen and Koster, 1989). Some of the factors are relatively static in time (eg topography, altitude and latitude), although the majority are time-dependent and closely interrelated. Another complicating factor is the relict character of a large part of permafrost which has no clear relationship to present day climatic parameters. This greatly complicates the assessment of the effects of climatic changes on permafrost as changes in different variables may either enhance or counteract each other.

Maps showing the distribution of permafrost are based on broad correlations with climatic data. For example, the 'southern limit' of permafrost is often represented by the -1°C mean annual air isotherm (Brown, 1978; Gavrilova, 1981), although occurrences of permafrost are known south of this (eg Zoltai, 1971). Investigators concerned with mapping permafrost at small geographical scales generally use a classification scheme in which permafrost is characterised as continuous, discontinuous or sporadic. Maps employing such classifications usually depict specific zones at different latitudes, although in reality there is a gradual transition from the seasonally frozen ground of temperate regions to the perennially frozen ground of the polar regions. The zones are meant to convey the relative areal dominance of permafrost and permafrost-free conditions.

Wherever the average annual temperature is within a few degrees of 0°C, local variations in surface conditions (vegetation, topography, hydrologic conditions, solar exposure and snow cover) determine where the ground thermal regime can sustain permafrost. Where conditions are not homogeneous, permafrost can occur in patches. At higher latitudes, where temperatures are lower, bodies of permafrost become more frequent and larger in extent. Even in very cold regions, however, there are still gaps in the permafrost, due primarily to the presence of water bodies (streams, rivers and lakes) which do not freeze to their bottom in winter. These non-homogeneous characteristics of permafrost coupled with the scattered nature of direct observations, make precise mapping of permafrost and ground thermal conditions difficult. They also make it difficult to develop an accurate geographic prognosis for permafrost responses to climatic changes.

Although there is broad and intuitive agreement about the concept of permafrost zonation, satisfactory operational definitions have not often been presented in the literature. This has lead to non-standardised mapping criteria.

Snow cover, through its influence on ground temperatures, can significantly affect permafrost occurrence. In discontinuous and sporadic permafrost areas, snow cover may be the critical local factor determining whether permafrost is present or not. In the colder regions of more continuous permafrost, it influences the depth of the active layer. A sufficient blanket of snow provides insulation to the ground, thereby keeping it warmer than that which would occur under less abundant snow cover or snow-free conditions. Goodrich (1982) concluded that mean annual ground temperatures are most strongly influenced by the timing of snow accumulation in autumn and early winter, and by the maximum depth attained over the winter. In his calculations, a doubling of the snow cover from 25 to 50 cm increased the mean annual surface temperature by several degrees. Rapid build-up of snow in autumn augmented this effect.

In some cases an abundance of snow may promote the occurrence of permafrost. Under these conditions the snow pack could persist until later in the spring or early summer. This delay would reduce the amount of warming of the ground that can occur (Gold, 1967; Goodwin and Outcalt, 1975).

Rainfall can also influence the permafrost by increasing ground temperatures. An increase in precipitation during the period when permafrost is not covered by snow tends to reduce ground surface temperatures due to associated cloud cover which reduces the incident solar radiation. Rain falling on snow also promotes the lowering of ground temperatures by reducing the insulating quality of the snow.

Vegetation and the organic layer play a role in the ground thermal regime in two ways: as part of a 'canopy above the surface, or as a surface layer over the mineral soil. A vegetation canopy reduces the amount of solar radiation reaching the ground surface, and will have a variable effect on the accumulation and persistence of snow cover (eg Luthin and Guymon, 1974; Gavrilova, 1978; Rouse, 1982). Interception of precipitation and transpiration by the canopy also influence the ground thermal regime through evaporation and the water balance. Rouse (1984) found that summer soil temperatures beneath an open spruce forest were lower than adjacent tundra as a result of radiation interception by the canopy, higher evaporation from the wetter surface and the greater roughness of the forest which increases turbulent heat loss to the atmosphere. Brown (1965) concluded that variations in the vegetation canopy were a relatively minor influence on the ground thermal regime compared to the surface organic layer.

The presence of sporadic or discontinuous permafrost is commonly associated with an organic surface layer, usually peat (Brown, 1973, 1978; Fitzgibbon, 1981). The particular influence of organic soils (especially peat) on permafrost is attributed to: (i) the low conductivity of organic soils relative to mineral soils; (ii) the effect of seasonal variations in the water content of organic soil on its thermal conductivity; and (iii) the seasonal evaporative regime of the surface as controlled by climatic and surface factors (Riseborough and Burns, 1988).

Seasonal variations in moisture content of the organic layer (thermal conductivity of peat 5-25 times that of wet or dry frozen peat) give it a low thermal conductivity in summer, inhibiting warming of the ground. In winter the wetter organic layer freezes, increasing its thermal conductivity thereby enhancing cooling of the ground. The mean annual ground temperatures under peat are, therefore, lower than under adjacent areas without peat, and permafrost can persist at sites with positive mean annual surface temperatures (up to approximately +2°C). Furthermore, the generally low thermal conductivity of surface organic materials helps to preserve relict permafrost beneath it.

In some areas at least, the direct effect of vegetation may be less important than its role in snow accumulation (Smith, 1975; Rouse, 1984). Where the canopy can trap a deep blanket of snow, the soil will be considerably warmer in the winter than in the nearby tundra (Rouse, 1984). Interception of snow by trees in areas of extensive boreal forest can reduce the snow cover (French 1976), lowering ground temperatures. Alternatively, a deeper snow cover may have a net cooling effect if spring snowmelt is prolonged, holding the ground surface temperature at or below 0°C when air temperature is high in early summer. The interplay of these factors contributes to the uncertainty over the precise implications of climatic changes for permafrost.

Permafrost does influence vegetative cover, although playing a relatively minor role compared to climate and soil type. The shallow active layer is a nutrient source for vegetation, maintaining water and nutrient supplies close to the surface. The permafrost layer is relatively impermeable and acts as a barrier to the movement of water and nutrients and restricts root growth to the active layer. Low active layer temperatures reduce nutrient availability and the rate of decomposition. Ecosystems such as black spruce and forest floor moss have adapted to the presence of permafrost and often sustain permafrost as well as being sustained by it.

Forest distribution near the tree line is commonly related to permafrost regimes (McKay and Baker, 1986). The abundant growth of mosses and the accumulation of undecomposed organic material at the surface in arctic regions provides insulation against summer thaw and increases soil moisture (Kryuchkov, 1978). In a study of forests and vegetation in the Mackenzie Valley, Zoltai and Pettapiece (1973) noted that taller trees were associated with deeper active layers, but die-off occurred when moss layers developed. Some species such as trembling aspen are restricted to areas where the permafrost table is well below the level of rooting. Other species such as spruce can grow on much thinner active layers.

Finally, permafrost as a climatic phenomenon is an indicator of both present and past climates. The upper layer (10-20 m), subject to annual temperature fluctuations, reflects current climatic conditions of an area - both regional (macroclimate) and site-specific (microclimate). At greater depths the temperature regime reflects the climatic conditions of earlier periods. Relict permafrost, usually found at significant depth, currently exists in regions which should be free of permafrost according to the present energy budget; therefore, it is normally unstable and slowly degrading.

Temperature records from oilwells and other boreholes in Alaska, Canada, Norway and Russia clearly show that the upper layers of permafrost (20-100 m) have increased in temperature over the past 50-100 years (Lachenbruch et al., 1989; Balobaev, 1985; Taylor and Judge, 1985). A very clear departure from the long-term geothermal gradient has been observed at depth. Although the historical record cannot be recovered as a unique solution, a surface temperature record can be determined (with decreasing precision for older events). The records display evidence of permafrost disturbance, though the driving mechanism is not necessarily a simple relationship with climatic changes. Lachenbruch and Marshall (1986) concluded that the deviations were due to an increase of the surface temperature in the range of 2°-4°C during the last century or so. This coincides with the amelioration of global temperatures since about 1850, following the Little Ice Age.

2.3.2 Responses of permafrost to climatic changes

Since permafrost is a thermal condition, it is sensitive to changes in climate. Additionally, permafrost to a large extent is inherently unstable, since it exists so close to its melting point and frequently contains large amounts of excess ice. Most permafrost in the discontinuous zone is either relict, or in a delicate thermal balance with its environment. Many thousands of square kilometres of permafrost are within 1°-2°C of the melting point and are particularly vulnerable to climatic warming. The overall effect of the projected changes in climate will be to raise the mean annual surface temperature, which will result in a deeper active layer with the permafrost table receding until an equilibrium with the new surface temperature regime is established. The base of the permafrost would also rise, though at a much slower rate. If the progressive warming were great enough, then the permafrost could eventually disappear altogether, although many centuries could be required for a complete thaw. Of more immediate importance would be various rapid-onset effects in areas of thaw-sensitive permafrost (that for which the potential for thaw and subsidence are great, and which contain up to 80% volume of ice in the upper 5-10 m). Global warming could cause the upper layers (0-5 m) to experience accelerated thawing, probably resulting in the disappearance of permafrost - on the order of decades. At the lower latitude margins of the permafrost regions, climatic warming will induce thickening of the active layer in areas that continue to be underlaid by permafrost. An example of the fairly rapid response of permafrost to climatic warming is the changes in the boundary of continuous/discontinuous permafrost in the Mackenzie Valley of several hundreds of kilometres in the late 1800s-1940s due to a temperature rise of 3°C (MacKay, 1975).

Most responsive to changes in climate would be those portions nearest the surface and potentially serious impacts are associated with the melting of shallow ground ice. If ice-rich permafrost degrades, widespread terrain disturbance and instability will be likely, including thaw settlement (up to several metres) and ponding of surface water (associated with thermokarst), slope failures (landslides) and increased soil creep. The associated thickening of the active layer (the layer of ground subject to an annual regime of freezing and thawing) would lead to a decrease in the stability of the surface. Even in colder, continuous permafrost areas, increased ground temperatures could lead to similar conditions of terrain instability, although there may not be any major changes in areal distribution of the permafrost.

In practical terms, increased terrain instability would lead to major concerns for the integrity of roads, airfields, dams, reservoirs and structural foundations located in affected areas. Thickening of the active layer would subject foundations to continuing deformations as a result of thaw settlement. Decreases in the amount of ground ice present would lead to decreases in the mechanical strength of the associated soil as well as increases in permeability, both of which will have significant consequences for engineering and natural processes.

Slope failures and thermokarst features would have detrimental effects upon local vegetation and could lead to significant decreases in plant species numbers and loss of sensitive populations. In the long-term, degradation of permafrost would allow the growth of deeper rooted, broadleaved species and the establishment of denser forests of coniferous species (Zoltai and Pettapiece, 1973). Over hundreds or thousands of years, species better adapted to warmer air and ground temperatures will tend to advance to higher latitudes. As the extent of the tundra shrinks, northern species may become less abundant as others replace them, potentially leading to the loss of some of the more sensitive plant species and ecosystems.

Changes in wildlife are generally dominated by many factors other than permafrost (see Working Group II Report, Chapter 3). Degradation of permafrost and its effects on vegetation and forests, however, will influence wildlife through disruption of the terrain, changes in surface hydrology and food availability. It is likely that these changes could both enhance and diminish species variability and numbers (Harington, 1986). For example, native arctic species such as muskox, caribou and lemmings might suffer due to changes in climate and to their ecology. A northward shift of the forests would reduce tundra and barrenlands species. Changes in wetlands may affect nesting areas and migration routes for waterfowl and other birds, as well as populations of insects and other wildlife native to these regions through potential losses and gains (thermokarst) in wetland areas. The overall impact on wildlife due to the expected permafrost degradation would be difficult to assess, especially considering the transient nature and rate of the expected ecosystem changes and associated changes in food and habitat availability.

The response of permafrost to a change in the surface temperature is a function of both the initial condition (ground temperature profile), thermal properties, and other factors (ie nature of the surface temperature disturbance, ice content and local heat flow). On an annual basis, heat transferred into the permafrost during the thaw season is removed during the freeze season and a stable permafrost table is established. A disturbance (such as a climatic warming) which introduces more energy during the yearly cycle without a compensating heat removal will cause the permafrost to reach a new equilibrium at a lower depth or to disappear entirely. As permafrost at todays depths is still adjusting to climates of past millennia, contemporary climatic changes may require thousands of years to alter the bottom of permafrost (Lunardini, 1981).

The effects of climate on permafrost temperatures depends on the relationships between air temperature, ground surface temperature, and the ground thermal regime. Ground surface temperatures are determined by the interaction between climate and surface conditions, while ground temperatures respond to the surface climate according to the thermal properties of the ground and the energy flows, phase changes etc. An increase in summer precipitation and temperatures would greatly increase ground surface temperatures (Goodwin et al., 1984). Wide variations in ground thermal conditions can occur within small areas of uniform climate, although in areas of little vegetation or snow cover the linkage between air temperatures and ground temperatures is more direct. The range in ground thermal conditions typically observed between sites in close proximity can be equivalent climatically to several degrees of latitude.

Climate warming will alter the annual temperature range in the ground, temperatures will warm least in that part of the year in which the ground experiences significant phase change (spring and autumn). Increased soil temperatures as a result of climate warming will penetrate slowly in warm permafrost, since the temperature change requires the absorption of significant latent heat of fusion (the entire latent heat of fusion for the soil if it warms above zero).

Changes in the buffering action of the surface layer (snow cover, vegetation, the organic layer and the mineral soil) will also be an important factor in determining the impact of climatic changes on permafrost. For example, where organic material is present, the permafrost would probably not degrade as quickly as at other sites, especially when combined with the effects of a forest canopy. Suggested increases in the incidence and severity of forest fires induced by climatic changes would accelerate permafrost decay.

Any changes in the surface properties or hydrologic conditions (such as those brought about by ecosystem changes concomitant with a change in climate) will undoubtedly have an effect on microclimatic conditions and thus ground thermal conditions. As a result, once permafrost degradation is initiated, thaw settlement can result in radical changes in the surface energy balance and the effectiveness of the buffer layer, accelerating further degradation.

The removal, damage or compaction of surface vegetation, peat and soil associated with changes in land use or catastrophic events can alter the balance of surface energy transfers, especially the rate at which heat can enter the ground. In general, these changes will lead to an increase in the mean summer surface temperature accompanied by deeper thawing of the active layer (Brown, 1963; Mackay, 1970), though soils under a disturbed layer can also freeze more intensively in winter (Gavrilova, 1973, 1978, 1981). Clearing and construction associated with the Norman Wells, Canada, pipeline right-of-way has caused a 2°C temperature increase in mean annual ground surface temperature compared to the adjacent undisturbed areas. Areas of sporadic permafrost have disappeared in northern Alberta, Canada, as a result of clearing, ploughing and planting.

Changes in snow cover accumulation, as suggested under various climatic change scenarios or that may result from creation of barriers, structures and depressions, or changes in vegetation cover or wind patterns, can lead to significant warming or cooling of the ground. The erection of snow fences has been shown to have an immediate warming effect on ground temperatures, maintained even against natural cooling trends. Gavrilova (1973,1978,1981) has found that similar disturbances to the surface cover can have opposite effects on the ground thermal regime in different regions or with differing sub-surface materials. However, the effects of surface environmental changes are usually restricted in areal extent, whereas climatic change, in contrast, can affect extensive areas of permafrost.

2.3.2.1 Changes in permafrost distribution

Climatic oscillations have caused significant degradation of the permafrost in the past (Danilov et al., 1985). For example, the multilayered permafrost in West Siberia consists of a relict part near its bottom, relatively new permafrost at the top, and a thick unfrozen layer with positive temperatures near zero separating them. Canadian and Soviet work (MacKay, 1975; Baulin and Danilova, 1988) document the fact that the areal extent of permafrost has changed over very long time periods. There is recent evidence for both aggradation and degradation of permafrost with studies showing the southern margins in retreat (Thie, 1974; Mackay, 1975; Hunter, 1988).

The problem of predicting the influence of climatic change on the future distribution of permafrost can be treated by examining the relationships between permafrost and climatic parameters. An ideal method for predicting permafrost response would consider the effects of macroclimate, snow cover, soil thermal properties, substrate variability, vegetation, and terrain complexity. Although scale dependencies may prevent a detailed depiction of the effects of parameters with strong local variations, their influence may still be discernible in a generalised manner (Nelson, 1986).

Nelson and Outcalt (1987) suggest that a 'frost number' based on frost/thaw depth ratio may be applied to the general problem of permafrost distribution and climatic changes. Stuart (1985) has demonstrated the validity of this approach. This index considers several important variables that influence permafrost, and can be computed using climate data that are widely available. Moreover, the index can be displayed in the form of readily interprétable maps.

The frost number uses freezing and thawing degree-day sums, or alternatively, freezing and thawing depths in the soil to régionalise permafrost on the basis of its continuity or discontinuity. Snow density, thickness, and duration, as well as soil thermal properties, are considered in the more elaborate variant of the model. Although vegetation has not been treated in any regional application to date, its effects could be taken into account in a generalised fashion through use of n-factor data (Lunardini, 1978). The limitations imposed by scale considerations on the inclusion of such effects should be kept firmly in mind, however, particularly in light of the fact that the frost number was devised to show broad relations over areas of continental dimensions. The frost number is also somewhat limited in its applicability to short-term climatic changes, owing to its implicit assumption of stationarity.

The frost number methodology was applied to the problem of examining permafrost distribution, subject to the limitation noted above, induced by climate warming for both permafrost regions and those with deep annual freezing within the territory of the USSR. For these purposes, the scenario of regional climatic changes derived from palaeo-based reconstructions was used (Budyko and Izrael, 1987).

The greatest changes in soil thermal regime are expected in the northern continental regions, whereas the near-coastal regions changes are not expected to be as pronounced. Under a 2°C global warming scenario (by the 2020s), active-layer thickening of 10% can be expected in continental situations exemplified by central Siberia, but only 5% in regions subject to oceanic influence (eg Kamchatka). Climatic changes will also increase the duration of summer, which may be very important for regions with deep seasonal freezing. Such changes may have a profound effect on enterprises such as agriculture.

Estimates such as those given above are valid only for the near-surface layer, as only seasonal freezing and thawing are considered. Changes in the thermal regime deep in the permafrost can be differentiated into two groups vis-a-vis global warming: i) a relatively fast reaction in regions where global warming fails to produce an inter-permafrost talik (a layer of thawed soil); and ii) slow thermal evolution when large amounts of heat are expended on phase changes in warm permafrost. These topics were addressed by Anisimov (1989a; 1989b), who employed a non-stationary model of heat and water transport in a stratified medium in conjunction with the climatic palaeo-based reconstruction method to estimate changes in the extent of permafrost in the territory of the USSR. The results of that study suggest up to a 10% areal reduction of the extent of continuous permafrost in the USSR over a 50-year period, given a 2°C temperature increase (Figure 7.3). Talik is expected to form between the top of the permafrost and the bottom of the active layer with the thickness of this melted layer increasing with time.

Palaeo-based reconstructions of the potential impact of the projected changes in climate have been developed using the Holocene climatic optimum (5000-6000 years bp) and the climatic optimum of the recent interglacial (125 000 years bp) as probable analogues of warming by 1°C and 2°C respectively (Velichko et al., 1990). This analysis suggests that significant changes can be expected in the areas from which the presence of permafrost retreat towards the poles. Permafrost degradation is expected with an associated increase in the thickness of the active layer. The southern contemporary boundary of permafrost could shift northward in those areas where the permafrost thickness is currently less than 25 m.

The actual impacts of the projected changes in climate are complicated by the influence of an expected increase in snow cover in much of the current areas containing permafrost. Recent observations of the response of permafrost to increase in temperature and snow cover (northern portion of Western Siberia during the 1940s) suggest that the maximum potential response of the permafrost during the next 2-3 decades to the projected climatic change may be one-half of that suggested by equilibrium analyses due to the influence of increased snow cover.

Under global warming of 1°C the most significant changes within the USSR are proposed for the southernmost portions of the permafrost with the boundary of the climatic zone which supports permafrost shifting northward and northeastward by 200-300 km. This will significantly expand the area of relict permafrost in western Siberia and the Pechora Valley. The boundary of the climatic zone which supports continuous permafrost will also recede approximately the same distance; however, in those areas where the ground temperatures are currently -5°C to -7°C continuous permafrost will be preserved. The thickness of the active layer (in loamy soils) is expected to increase by no more than 0.5 m.

A 2°C global warming (projected for 2020s) will shift the southern boundary of the climatic zone which supports permafrost over most of Siberia north and north eastward by no less than 500-700 km from its current position. In the north of Eastern Europe only relict permafrost will remain. The climatic zone supporting continuous permafrost will disappear from Western Siberia and will be restricted to north of the Arctic Circle in Eastern Siberia. The depth of the active layer (in loamy soils) is expected to increase by nearly 1 m (Figure 7.4a).

Within Canada under a 1°C and 2°C increase in global temperature, responses within permafrost similar in magnitude to those for the USSR are suggested (Velichko et al., 1990). The southern boundary of the climatic zone supporting permafrost is expected to move poleward by approximately 200 km and 700 km, respectively. Expected increases in the depth of the active layer of 0.5 m and 1 m, respectively, are similar to those proposed for the USSR. Permafrost will be preserved at latitudes of 66°-68° N where low mean ground temperatures of -5°C to -6°C will persist even under a global temperature increase of 2°C (Figure 7.4b).

Goodwin et al. (1984) examined the impacts of 3°C and 6°C increases in temperature at two locations within Alaska: Barrow (continuous permafrost) and Fairbanks (discontinuous permafrost). At Barrow, primarily as a result of higher summer temperatures, the thickness of the active layer increased 41% and 71% respectively. At Fairbanks, the depth of the active layer increased 11% and 24% respectively with winter temperature apparently playing the dominant roles.

Osterkamp (1984a; 1984b) discussed quantitatively the potential impact of climatic changes on permafrost and the time scales involved for various regions of Alaska. Under a ground temperature increase of 3°C, a general warming is expected to occur in the continuous permafrost zone causing the permafrost to thaw at its base until it thins and a new equilibrium is reached (several thousand years). In the case of both continuous and discontinuous permafrost, thawing from the top and base may be expected. Generally, permafrost with a thickness of approximately 25 m is expected to completely thaw over about 200 years.

Projects developed in China (Ruqiu, 1990) suggest that over the next 10-20 years a 0.5°C increase in mean global temperature would result in a 5% decrease of the permafrost and that a 2.0°C increase would produce a 10-50% decrease. Under this latter scenario, major portions of the large and continuous areas of permafrost in China would no longer exist.

A mean annual warming of 2°C may have significant effects on the extent of permafrost ice on Mexico's higher peaks (Menchaca and Byrne, 1990). Disappearance of existing ice fields, although currently not larger than 5 km, would have important consequences for the hydrology and ecology of local streams and perhaps local climatic conditions (eg cold air drainage).

2.3.2.2 Implications of permafrost degradation

Global warming could result in an increase in the depth of maximum thaw (permafrost table) and a general warming of some thickness of the permafrost, even if the permafrost itself does not thaw. However, if the global warming also disturbs the buffer layer (eg increase in snow depth or duration) the effect on the active layer may not be reliably predictable. The active layer is the zone where many damaging phenomena such as frost heave and thaw settlement are most significant. If the active layer increases in thickness, it will probably compromise the foundation designs of existing engineering systems founded on permafrost and can cause mechanical disruption of roots. Active layer growth will also mean an increase in the temperature of the remaining permafrost with the attendant operational difficulties associated with the decreased strength of warm permafrost.

An increase in the temperature of frozen ground will result in changes in mechanical properties, in particular soil strength and deformation characteristics. This will adversely affect the stability of slopes. Natural processes such as slumping, solifluction, and icing (ie sheet of ice on the ground surface as the result of groundwater seepage) can all be expected to accelerate. In mountainous areas such as Tjan Shan and Pamir in Central Asia, the thawing of moraines and stone glaciers could destroy structures (eg communication towers) located on slopes. The adverse effects of such phenomena are abundantly in evidence and give ample warning of what to expect in the permafrost regions should the expected global warming occur.

A critical feature of some permafrost is the presence of massive ice (which may be detected and mapped using ground probing radar). When melted, the areas which have these deposits could experience land subsidence, shoreline retreat, and lake formation, directly related to the amount of ground ice and its thaw rate (Schur, 1974; Grigorian et al., 1984). The failure of ice-rich riverbanks and slopes (Lawson, 1983) would be accelerated by general permafrost degradation. Although the interaction between permafrost and bank erosion is not well understood, it seems likely that in the short term thawing permafrost would aggravate streambank erosion. In the long term this erosion will not be significant in areas where the permafrost has disappeared.

Soil erosion can be acute when the soil is finely textured and there are high quantities of melting ground ice (Linell and Tedrow, 1981). Where slopes are steep, solifluction and mass-wasting can be very significant erosion mechanisms. Degrading permafrost in ice-rich areas will increase natural erosion.

In regions where the top of the permafrost (permafrost table) is lowered as a result of thawing, available soil moisture may eventually be decreased. In some areas, water is kept near the surface by a relatively impermeable layer of ice provided by the permafrost table. Existing vegetation can tap this moisture, with roots extending throughout the active layer. With the degradation of the permafrost, the permafrost table will retreat to lower depths in the soil or, may even disappear altogether. Water may no longer be trapped near the surface, reducing the amount of moisture available to the overlying vegetation. The forest (taiga) in Central Yakutia (Siberia), for example may become more desert-like if the permafrost table lowers. Serious drying could occur in areas of plateau permafrost in China, leading to a degradation of grassy marshland. In some portions of the plateau permafrost a desert-like low-temperature plateau area could develop and existing pasture land areas could decrease.

Permafrost is a product of climate, but it in turn influences climatic conditions through the heat and water balance near the surface, in air and in soils. Frozen soils absorb a great amount of heat during active layer development (thaw) in summer. Frozen soils also retain large amounts of moisture. Deepening of the active layer and increase in soil temperature will bring large volumes of water-bearing soils into the local water and energy balances in the short term. Increased evaporation may alter the areal, temporal aspects and types of cloud cover which could significantly effect the overall energy balance.

2.3.3 *Gas hydrates and methane*

Gas hydrates can form in places where gas and water exist under high pressure and low temperatures. In the case of permafrost, these conditions can exist within and beneath the permafrost and solid crystals of gas hydrates can be found. Although gas hydrates were observed in Siberia in the early part of the 20th century, only in recent years has active interest been focused on whether they are widespread in permafrost regions. Because of their potential impact on climate warming it is important to consider where such deposits may exist and how they may be affected by the projected changes in climate.

Evidence exists that degradation of permafrost as a result of the projected GHG-induced changes in climate will result in an increase in atmosphere. Degradation of permafrost will subject previously frozen biological material to rapid oxidation and large scale release of methane, and to a lesser extent CO_2 (Billings et al., 1982) into the atmosphere. In addition, significant quantities of methane within gas hydrates (Kvenvolden, 1988) that are trapped within and beneath permafrost will provide large amounts of this greenhouse gas to the atmosphere as degradation proceeds. Of the various sources of methane on the earth, the most uncertain is that connected with gas-hydrate formations and their degradation.

In the USSR, gas hydrates have been found in the Messoyakha gas field of western Siberia (Makogon et al., 1972), Timan-Pechora province, the eastern Siberia craton, and in the northeast and Kamchatka areas (Cherskiy et al., 1985). In the North American Arctic, hydrates are known in the Mackenzie Delta, the Sverdrup Basin, the Arctic Platform and the Arctic Islands (Judge, 1982), and in the North Slope of Alaska (Collett, 1983). A summary of the gas hydrate estimates of various authors (Table 7.4) was adapted from the Potential Gas Committee (1981).

Table 7.4 Estimates of methane hydrate resources within permafrost regions (adapted from Potential Gas Committee, 1981)

Volume m^3	**Mass** GT (10^{15}g)	**Reference**
	OCEANIC	
3.1×10^{15}	1.7×10^3	McIver (1981)
$5\text{-}25 \times 10^{15}$	8.0×10^3	Trofimuk et al. (1977)
7.6×10^{18}	4.1×10^6	Dobrynin and Koratajev (1981)
	CONTINENTAL	
3.1×10^{13}	1.7×10^1	McIver (1981)
5.7×10^{13}	3.1×10^1	Trofimuk et al. (1977)
3.4×10^{16}	1.8×10^4	Dobrynin et al. (1981)
	4.0×10^2	MacDonald (1980)

Estimates of annual methane release from hydrates over periods of several decades varies between 5 Tg/year (Cicerone and Oremland, 1988) and 160 Tg/year (Kvenvolden, 1988), the largest component in all cases being derived from areas of offshore permafrost. Hydrates contained in terrestrial permafrost are considered to be effectively isolated from warming, and would require centuries for temperature changes to affect them in any appreciable way.

The contribution of methane derived from gas hydrates may lead to an additional 0.4°C increase in global temperature by the 2020s and 0.6-0.7°C by middle of the 21st century, when atmospheric methane concentrations are expected to be twice those in the pre-industrial period. There is reason to expect that the positive feedback between climate and methane hydrates in permafrost may be even stronger than this. Owing to photochemical reactions between minor atmospheric constituents, an increase in the concentration of atmospheric methane will cause an increase in its lifetime in the atmosphere, and the greenhouse effect produced by this gas could therefore be higher.

The qualitative analysis presented above demonstrates that hydrate-climate interactions will indeed result in positive feedback and intensification of the greenhouse effect within the atmospheric system; owing to the many uncertainties and quantitative disagreements between authors, only a sign and an order of magnitude for this effect may be stated with confidence now. Further investigations are needed urgently to refine this.

2.4 Seasonally frozen ground

Seasonally frozen ground occurs in those areas where the ground temperatures drop below 0°C only during some portion of the year (ie some fraction of the winter months). Frost penetrates the ground from the surface as the energy balance lowers ground surface temperatures to below freezing. The depth of frost penetration is controlled by several factors, primarily air temperature, the nature of the surface cover, water content in the soil and the thermal characteristics of the soil and snow cover. To a large extent, the physics associated with seasonally frozen ground are analogous to aggradation and degradation of permafrost with the major difference being that, in the case of permafrost, the ice persists throughout the year. The role of the 'buffer' layer in the dynamics of the frozen ground, however, is similar.

Global warming will affect the areal distribution of seasonally frozen ground and the depth of frost penetration. With warming and if other factors are essentially unchanged, the area experiencing seasonally frozen ground will be reduced and, for those areas where the ground will still experience annual freezing, the depth of penetration will decrease. As in the case of permafrost, changes to the buffer layer (eg snow cover and vegetation) as a result of climatic changes could influence the responses in some locations due to the net effect on the local surface energy budget.

The impact of the projected changes in climate on frost penetration can be illustrated using empirical estimates based on degree days below 0°C. Calculations shows that for two locations in Canada, one a relatively cold location (Calgary, Alberta) and the other a more temperate location (Toronto, Ontario), frost penetration will be reduced significantly by 50-60% and 75-85% respectively as a result of an increase of 6°C in the mean annual air temperature (Brown, 1964; DOT, 1968).

Regions experiencing seasonally frozen ground undergo many of the same detrimental effects noted for the permafrost zones and commonly support large populations, especially in North America. Reduction of the area experiencing seasonally frozen ground or in the depth of frost penetration would have significant positive ramifications especially for the agriculture and construction industry.

3 Socioeconomic consequences

3.1 Seasonal snow cover

Despite the transient nature of seasonal snow cover, it plays an important role in the earth-atmosphere system both in a biophysical and a socioeconomic sense. Seasonal snow cover (along with mountain glaciers) is a vital water resource for irrigation, hydroelectric power generation, agriculture and potable water. There will be detectable changes in river flow regimes from the projected changes in snowfall and melt patterns. This would result in increased winter runoff in some regions owing to higher temperatures and a greater percentage of precipitation falling as rain. Less water would be available during the summer months in those regions which rely on snowmelt. These suggested changes could decrease the annual amplitude of river discharges with water management benefiting as the demand for regulated storage decreases (Eriksson, 1989).

This change in runoff regime will have repercussions for hydroelectric power generation. Hydro projects such as those in eastern Canada at La Grande (Quebec) and Churchill Falls (Labrador) which fill their headponds from the snowmelt water accumulated over the eight-month subarctic winter will be significantly affected by changes in snow cover and melt. Particularly sensitive are those areas for which snow melt supplies a major proportion of the water resources. This includes areas of the Alps and Carpathians of Western Europe, the Altai and Tjan-Shan Mountains of Central Asia, the southern Andes in Argentina and Chile as well as in numerous parts of the Western Cordillera of the US, to cite a few examples.

Computer simulations show desiccation of large areas of the mid-latitude agriculturally productive areas in the northern hemisphere (Schlesinger and Mitchell, 1985). This summer drying is, in part, due to the earlier spring melting of the seasonal snowpack. This has implications for many regions of the world adjacent to snow-rich mountain water supplies that recharge major rivers and groundwater reservoirs. For example the South Saskatchewan and North Saskatchewan Rivers in the Canadian Prairies maintain strong base flows even in drought years because their principal sources are in the Rocky Mountains. Similarly the Syr Dar'ya and the Amu Dar'ya Rivers passing through dry regions of the Central Asian republics of the USSR to the Aral Sea are fed from snow supplies in the Hindu Kush and neighbouring mountain systems.

As a consequence of projected changes in snow cover in New Zealand, the seasonal flow of rivers would change markedly, with major ones like the Clutha and Waitaki having 40% more flow in winter and 13% less flow in summer, although the latter could be further augmented by meltwater from diminishing glaciers. Annual runoff could increase by 14%. On smaller mountain streams, vital for local irrigation, the lower snow storage will probably lead to decreased summer flows when some will dry up.

Survival of over-wintering agricultural crops such as alfalfa, winter wheat and perennial forage legumes in cold climates is linked to whether or not a persistent snow cover exists during the winter months. Periods with warm temperatures and rainfall which melt existing snow cover and result in a dehardening of over-wintering crops commonly result in significant losses (up to 30-40% on average for forage legumes and winter cereals in the Canadian Maritime Provinces, Suzuki, 1989). Changes in the frequency of these warm air intrusions would place these crops in a vulnerable position should the temperatures subsequently drop quickly below freezing. In addition, because of the bare ground with a freeze-thaw cycle, soil heaving and soil cracking could be extensive, jeopardising tap root crops such as alfalfa and exposing underground tissue.

Seasonal snow cover is vital for winter tourism and recreation. In southern Quebec, Canada, it has been estimated that as a result of the GHG-induced climatic changes the number of days suitable for skiing would decrease by half or more, representing losses of tens of millions of dollars annually to the economy. The situation in the south Georgian Bay area of Ontario could be worse with the virtual elimination of a $50 million annual downhill ski industry with impacts on associated suppliers.

Of particular concern to winter tourism is the economic consequences of a change in the seasonal distribution of snow cover. Should the start of the snow cover season be delayed until late December or January, winter tourism (eg skiing industry) would lose one of its most profitable periods (ie Christmas and New Year).

Tourism will be both positively and negatively effected by suggested changes in snow cover (Chinn, 1989). Less spectacular glacial and winter scenery may decrease the number of tourists; however, a more agreeable climate and easier access may encourage touring and hiking activities as the environment would be less demanding.

Changes in seasonal snow cover will have repercussions with respect to snow removal costs and vehicular accidents. At Toronto, Ontario (Canada), a comparison was made between 1981-82, a near normal snowfall winter, and the succeeding year 1982-83 which received 52% of normal snowfall (Rowe, 1984). Snow removal costs on roads, at the airport and at public buildings were reduced to near 60% during the more open winter. Costs of vehicle accidents attributed to weather were reduced to 55% of that incurred during the snowy winter.

Avalanche activity is one type of catastrophic event that may be affected as a result of climatic changes and potential changes in snow pack quantity and quality. Avalanche control is an expensive proposition, although justifiable based on the costs associated with lack of control.

The fact that avalanches are also influenced by terrain and weather conditions adds complexity to the relationship between climate and avalanche activity. Data analysis of avalanches for the period 1800 to 1985 does not show any temporal trends (Fohn, 1989). An analysis of the period from 1885 to 1985 suggests that avalanche activity is associated with nine specific weather types. Projections of the frequency of these specific weather types under conditions of climate warming are required in order to assess effects on avalanche activity.

Rogers' Pass in the Columbian Mountains of the Canadian Rockies averages approximately 38 major avalanches (more than 0.3 m of snow on the road) per winter. In addition to operational costs of monitoring and control (approximately $200,000 annually in Banff National Park), these events can result in increased costs through clean-up related expenses and costs associated with re-routing or delays for transportation (road and railway).

3.2 Glaciers and ice sheets

In many parts of the world glacier runoff makes a significant contribution to the total water resource. Glaciers contain an enormous reserve of water equivalent to precipitation over the entire globe for about 60 years. Possible effects of climatic changes on availability of glacier runoff water should be taken into account in long-term water resource planning. The disappearance of 8.3 km^3 of water over the next 70 years as a result of glacial retreat in Austria (Kuhn, 1989) will contribute to the runoff of the Danube, Drau, and Rhine Rivers to the extent equivalent to only one 100 mm rainfall evenly spread over the entire country, or little more than 1 mm/year. For example, glacier retreat in the Susitna River basin - Alaska, where a major hydroelectric faculty has been under consideration - has been large, and may increase as a result of climate warming. The availability of glacially derived water in the future needs to be considered.

In New Zealand over 70% of the electricity is produced by hydroelectric generation (Fitzharris, 1989). Under present conditions glaciers contribute to about 10% of the summertime flow in certain western rivers. Models indicate that a 3 °C increase in mean annual temperature could result in a 10% increase in electricity production on an annual basis and would reduce water storage requirements. Changes in water management strategies would be required.

The projected decrease in glacial coverage could increase the incidence of debris flows (Zimmermann and Haeberli, 1989). Uncovered debris masses on steep slopes have been exposed to erosive processes during the recent retreat of glaciers (Church and Ryder, 1972; Quilty, 1989). This debris has been responsible for the partial and complete burial of structures, traffic routes and vegetation and is commonly deposited in rivers obstructing their flows and increasing sediment loads. Increases in the amount of exposed debris are likely as glaciers retreat under the influence of projected climatic changes, thereby increasing the probability of debris flows.

Research in Scandinavia suggests that projected temperature increases will cause enhanced glacier retreat and increased discharge into rivers which carry glacier meltwater (Karlen, 1989). Severe flooding of these river basins is not expected if the mean summer temperature increase is of the order of 1.6°C, however, if the mean summer temperature is increased by 5.5 °C over a relatively short period of time, heavy flooding could occur.

3.3 Permafrost

Communities at high latitudes have adapted with varying degrees of success to the presence of permafrost. The effects of permafrost warming on these communities will depend on the relationships between the natural environment (including permafrost) and the various structures and facilities that make up the community. Although many anticipated impacts of permafrost degradation are negative (including the possible relocation of whole communities), positive impacts are also foreseen, especially in the long term after the near surface layers have achieved some measure of equilibrium with the climate.

Construction on permafrost has been dealt with by building on its strengths and reducing its weaknesses. Heated structures in permafrost are usually designed using one of four approaches:

i) Disregard the thermal regime of underlying permafrost, and apply conventional techniques of temperate regions. This assumes that thawing of the permafrost will have no adverse effect on the structure. This is a risky design approach on thaw-unstable permafrost for all but small or short-lived structures. Where appropriate, this approach would be unaffected by climatic change.

ii) Thaw permafrost before construction. This approach is expensive and not used widely, except in the mining industry in Alaska (Sanger, 1969) and Russia (Bakakin and Zelenin, 1966). The procedure is limited to the discontinuous permafrost regions. It is possible that climatic warming may eventually lead to more widespread use of this design technique.

iii) Allow for thaw during the construction and operation of the structure. In the discontinuous permafrost zone where consolidation and thaw must be expected the permafrost may, under very special conditions be allowed to thaw during and after construction. The method should be used only where the foundation materials are thaw-stable or where expedient or short-term construction is involved. Generally, the design must allow for differential thaw and settlement. Although the Soviet Building Code (1960) lists the depth and rate of thaw allowable, the prediction of differential settlement is so unreliable that the entire procedure must be considered risky. Climatic warming would add new uncertainties.

iv) Maintain the permafrost in a frozen state. One of the most common design techniques presently used is to prevent thawing of the permafrost by maintaining the permafrost table and temperature for the life of the structure. This technique, which is vital in continuous permafrost, is now widely used in Canada, USSR and the US. Climatic change would cause problems for those structures founded on permafrost which would not be sustained under a new climatic regime.

Existing foundations designed on the principle that the ground remains frozen for the life of the structure will require modification. Pile foundations in permafrost rely not only on the ground being frozen but the bearing capacity of individual piles is a direct function of the temperature of the frozen ground. Permafrost can lose more than half of its strength when warming close to the freezing point without thawing; actual thaw can reduce its bearing capacity to practically zero. Thickening of the active layer will mean an increase in the length of pile affected by seasonal frost action. Thus, any changes that can produce a warming of the permafrost can have a significant effect on such piles, within the life span of the structure. Structures will have to be redesigned to accommodate such warming where possible, or resort to refrigeration systems to maintain freezing temperatures.

Permafrost warming or degradation, increased depth of seasonal freezing and thawing and associated increases in frost heave forces (Esch and Osterkamp, 1990) will result in an increase in the maintenance requirements of facilities founded on permafrost. When maintenance costs become excessive it may be necessary to retrofit existing facilities for economic reasons. Such remedial measures could include presently available methods such as supplemental freezing of the foundation materials, stiffening or replacement of the supporting structure, adding earth materials, insulating materials etc. Each type of facility will require retrofitting schemes tailored to preserve its function. Retrofitting and maintenance programs will require the use of existing techniques and the development of new maintenance methods.

Bridges, buildings and utilities founded in thaw-sensitive permafrost would experience an increased rate of settlement with any increase in permafrost temperature, due primarily to the creep of the frozen soils. The rates would be greatest in fine grained (silt or clay) ice-rich soils. Facilities on thaw-stable materials would be affected minimally by a rise in temperature. However, many structures are located on ice-rich permafrost soils and most utility lines (water, sewer, steam etc) traverse ice-rich soils and even ice wedges. The thawing of this permafrost would result in large total and differential settlements. Even minor settlement can render doors, windows and other structural features essentially useless. Differential settlements would cause large internal stresses in the structure which could result in large distortions or even collapse. Utility lines could rupture where large differential settlements occur. These lines are particularly vulnerable where they enter or approach a structure undergoing significant settlement or where they traverse thaw-sensitive slopes. Thawing sensitive permafrost slopes could break portions of the lines away from portions founded on the stable soils or bedrock.

Monitoring programs will be needed in order to avert property damage, possible loss of life, and environmental degradation. Observations of soil temperature as well as of the movements of the structure and the surrounding earth would be required. The results of the observational program should provide guidance for instituting remedial measures that would minimise damage and avoid loss of life.

Monitoring of sensitive structures during the period of transition from permafrost to non-permafrost or for those structures not designed to adapt to degradation of the permafrost as a result of climatic changes will be expensive. For example, improper installation of wooden piles for a building in Fort Franklin, Northwest Territories in Canada (1985) necessitated introduction of a monthly monitoring program, which cost $120,000 over a two-year period.

Existing water-retaining structures founded on permafrost and subjected to an increase in temperature will suffer two serious consequences. First, the risk of water seepage through the foundation will be increased due to thaw in the foundation (as a result of the altered heat balance between the permafrost and the reservoir water), allowing seepage beneath the dam. Heat transported by the flowing water will accelerate thaw, exacerbating the seepage problem. Loss of water can have serious economic consequences where the water is being stored for human consumption or for use in industrial processes. Second, if the foundation materials are thaw sensitive, a catastrophic failure could occur owing to the reduction in strength when the frozen materials are thawed. The failure of dams retaining water could result in the loss of life and property downstream in addition to the economic loss of the dam and reservoir. To guard against the failure of a dam, extensive monitoring of dam and ground temperatures will be required, as well as measurements of seepage and ground movements. The natural earth slopes surrounding the reservoir would require monitoring for movement and temperature changes as well.

Current mining projects in areas of thaw-stable permafrost would be unaffected by permafrost degradation. Mines in thaw-sensitive areas, such as the Polaris mine near Resolute (Canada) have been designed to take advantage of the ice-rich permafrost (Giegerich, 1988), and degradation could create major problems there. In the Svalbard, Norway area there are currently no water problems in the mines due to the depth of the permafrost (200-300 m), although there is water under the glaciers (taliks) (Liest0l, 1976).

Mines such as Red Dog in Alaska, developed in ice-rich and warm permafrost regions, experience significant engineering problems related to stability and leaching (Giegerich, 1988). Permafrost degradation could only increase these problems over the short term. In the Isfjorden, Norway area, increased temperatures may affect the permafrost and create problems for mining only in the long term as thawing would take more than 100 years. In general, though, mining tends to occur in dry permafrost regions, and the melting of ground ice would not be significant (McKay and Baker, 1986). The release of methane from thawing permafrost could possibly be a health and safety hazard due to its poisonous and explosive nature.

Several changes are predictable as climatic changes influence the frozen ground in and around mine sites. The first change, while not a change in permafrost, will have significant effects on any mine which depends upon winter roads for supplies and back haul of product or other bulky materials. The snow road season will be shortened and the cost effectiveness will diminish. Conversely, increased precipitation as snow will ease the building of winter roads in areas where snow is presently in short supply. The Lupin Mine of Echo Bay Mines measures its savings from using winter roads in the millions of dollars each year.

The mining, blasting and handling characteristics of unfrozen ore are better than those of frozen ore. It is difficult to imagine, however, that climatic changes would have economically measurable effects when the duration of any one mine is considered and the more immediate thermal effects of shipping, blasting and moving ore are contemplated.

Of greater significance is the potential stability of mining structures which may persist beyond the economic life of the mine. These include waste dumps, tailings dams and water diversion channels. The stability of any or all such structures could diminish with increasing ground temperatures particularly if coupled with increased precipitation and runoff during the spring freshet. Increased precipitation plus increased ground water from the thickened active layer would increase costs of water management in open pit mines. In addition, the tailings pond management costs would increase as additional water handling and management would be required.

The complex subject of acid mine drainage in a permafrost environment could be affected by thermal and precipitation changes. More water from precipitation or permafrost degradation or both would increase the probability of acid generation at acidic mine sites. To the extent that receiving waters would have increased flow from non-acidic environments, however, the changes could be neutralised. Any increase in acidity would increase treatment costs.

In summary, the changes to the socioeconomic setting for surface mining would be measurable in several different ways but whether the net change would be positive or negative would depend upon local conditions and the degree of thermal change at any one mining operation.

Existing underground storage cavities and rooms in permafrost soils would be subject to accelerated closure due to creep of the frozen soil when warming occurs. If the temperature rises above the melting point of the permafrost, the underground openings would most likely collapse. The stability of the openings in the thawed soil would depend upon the type of soil (clay, silt, sand or gravel) and its thawed strength. The rate of closure of an opening in permafrost increases with temperature, moisture content (ice and unfrozen water in permafrost), the magnitude of the applied stress, and the dimensions of the unsupported opening. Local meat cellars in native villages may flood with increased precipitation and thaw.

Solid waste disposed of in a sanitary landfill site on permafrost subsequently freezes, so that decomposition occurs only slowly over the summer periods. The near-impermeability of permafrost ensures the isolation of leachate from local groundwater. Permafrost degradation could create a health risk at existing waste-disposal sites due to leaching and subsequent contamination of groundwater where the groundwater is no longer isolated from leachate by permafrost. Most governments will find it necessary to prohibit the practice of land application of liquid waste and to require that previously disposed toxic wastes be removed from areas where permafrost is degrading.

Some of the more important implications of changes in permafrost are found in transportation networks. The development of thermokarst ponds and the thawing of ice wedges and changes in patterned ground upon warming of permafrost would reduce the accessibility of many areas. There would be negative impacts on many existing road and railroad networks and airstrips. In addition, permafrost terrain is particularly sensitive to vehicular traffic, which can alter the surface and may induce thermokarst features or alter vegetative growth (Richard and Brown, 1974). In the short term, the sensitivity of natural surfaces would probably increase. This problem will eventually disappear in areas where permafrost degrades completely.

Long linear structures such as highways, airfields, transmission lines and pipelines must deal with a variety of design and construction conditions in that they traverse nearly all types of permafrost and non-permafrost conditions. An increase in the average annual temperature would cause the depth of seasonal thawing to increase to greater depths near these facilities since much of the insulating vegetation has been removed from these areas during the construction of the facilities.

In the areas where the soils consolidate upon thawing, transport facilities could experience uneven settlements, as well as lateral movements at locations where the facility traverses sloping terrain. Conditions would be aggravated where drainage systems are disrupted by earth movements. If the drainage system were left uncorrected, water could pond near the facility and also run uncontrolled in the vicinity causing erosion and increased subsidence near and within the facility. Pavements would undoubtedly be fractured and the traffic supporting surface could become rough enough to be unusable if uncorrected. The possible risk of pipeline rupture and the accompanying environmental degradation would be increased in areas where the pipeline depends upon permafrost for support. As a result, the amount of maintenance required to keep these types of facilities operational would increase significantly. In many locations where thaw-sensitive soil is traversed it may be necessary to relocate airfields, highways and pipelines. In the case of either a hot or a chilled pipeline, it may be necessary to change operational procedures.

Some examples of the costs associated with repair and retrofitting of these types of structures are indicated by the following.

i) Electrical power transmission line extending 900 km from Saskatchewan to Nelson River area through the discontinuous permafrost zone south of Winnipeg, Manitoba in Canada. By 1974 the effects of frost action had necessitated repairs to the foundations of transmission towers totalling $2 million (1974). Power outages on the line imposed another $20,000 an hour and had an immense economic and social impact on corporate and domestic consumers.

ii) An unusually warm summer in 1989 caused major thaw settlement of the portion of the Deadhorse, Alaska, runway. Costs for remedial work on the runway is estimated to reach $440,000 and costs to rebuild the runway to overcome current thaw settlement problems is estimated at $6-8 million.

iii) Maintenance for roads on unstable ice-rich permafrost costs about $5000/year/mile more than roads on stable ground.

iv) The Northwest Territories in Canada has a total of 2000 km of all season roads and another 2000 km of winter roads and plans exist to build another 2000 km of all season roads. Construction costs are estimated at $200,000 to $300,000/km within the Mackenzie Lowland Area and $450,000 to $600,000 in the Precambrian Shield Area. It is estimated that designing to include the effects of the projected climatic changes will double these costs.

v) Alaska has 2300 miles of road of which 60% are in relatively warm discontinuous permafrost terrain. In recent years, 98 miles of highway have had chronic permafrost thaw settlement problems requiring frequent patching and levelling efforts while an estimated 340 additional miles will require eventual reconstruction to re-level sags, dips and spreading cracks at a cost of $150,000 to $200,000/mile. Repairs to 100 m of the Dempster Highway, Northwest Territories, where a large ice wedge thawed and a truck fell into the hole, killing the driver, cost $100,000 in engineering studies and $150,000 in repair work.

At present there is very little agriculture in northern high latitudes, although farming can be of significant local importance. The controlling factors on agriculture are many, and include climate and soil properties. Soil temperatures are critical, and summer values of less than 8-11°C prohibit agricultural crops. Much of the heat entering the ground in permafrost is required for thawing, thus keeping ground temperatures low. Linell and Tedrow (1981) conclude that agriculture on permafrost is usually not feasible, with the exception of greenhouse- or livestock-based agriculture. Agricultural prospects are limited for a variety of reasons, of which permafrost is only one and not the most significant. Studies reported by Dinkel (1984) suggest, however, that in some areas only slight increases in air temperature would result in greatly improved crop potential at the latitudes of Alaska.

Warming permafrost would benefit crop development by increasing active layer thickness and water availability, although degrading permafrost in ice-rich areas will probably increase natural erosion. Permafrost recession below the active layer would eventually allow summer active layer temperatures to rise more than at present, but reduce moisture availability. Warmer soil temperatures would extend the crop growing season.

Thermokarst features are favourable for crops in moisture-deficient environments. These depressions tend to have a more favourable moisture regime for crop growth than higher areas, in part because they tend to accumulate runoff. The melting ground ice creating the depression could act as a water resource for the crops. Thermokarst features are used to agricultural advantage, especially in Siberia and the Far East (Linell and Tedrow, 1981).

Hunting and trapping are a valuable food source for local northern communities, as well as a source of income. In 1982-83 they provided almost $3 million of income to the Northwest Territories (McKay and Baker, 1986). Hunting and trapping as well as forestry and agriculture would tend to be enhanced as permafrost degrades or disappears.

3.4 Seasonally frozen ground

Large portions of the world's population live in areas which experience seasonal frost. Decreases in the extent of areas experiencing seasonally frozen ground, and in the depth to which it penetrates, will be beneficial as costs of construction and maintenance of structures and the area experiencing frost heave and related crop damage are reduced.

Within the province of Ontario, Canada highways which experience seasonally frozen ground normally are repaired within 10 years of construction due to damages resulting from frost heave. The cost of this repair is estimated at $5000 -$10,000/km.

4 Future deliberations

Projected changes in climate will alter the distribution of seasonal snow cover, ice and permafrost. On a global scale, the areal extent of seasonal snow cover and permafrost will decrease as temperatures warm. Snow will move to higher latitudes and elevations and existing permafrost melting and boundaries retreating towards the poles. The global distribution of glaciers and ice sheets is also projected to decrease, however, their responses are complicated by projected increases in snowfall in some areas (eg over Greenland and Antarctica) which could contribute to the growth of some glacier and ice sheets. Secular climatic trends are clearly reserved in mass and temperature changes of glaciers and permafrost, which is mainly due to the slowness of heat diffusion and the retarding effect of latent heat exchange. Therefore, the analysis of permafrost temperature as a function of depth appears to yield a temporally integrated record of air temperature changes in the past.

The uncertainties in our understanding of the dynamics of seasonal snow cover, ice and permafrost are large. Our knowledge of snow accumulation rates, ice-shelf bottom melting rates and calving rates in Antarctica is significantly limited. Similarly, we have a poor knowledge of the ablation rates in Greenland and, even worse, calving rates there. Thus, we cannot say how these ice sheets will react until we know more about their basic dynamics.

Systematic monitoring of climatic and seasonal snow cover, ice and permafrost conditions at a regional scale is required to identify trends, to provide data necessary to increase our understanding of climate relationships and to assist in defining likely responses to changes in those conditions. Such data could be used to develop, refine and verify models of those relationships, and would also extend our knowledge of current distributions of seasonal snow cover, ice and permafrost and their dynamics.

Uncertainty exists on how proposed global changes will be reflected at the regional and local levels. This uncertainty stems in part from the lack of knowledge of climatic changes at these scales. Current generations of GCMs are not able to provide sufficient detail on how regional and local climates will change as a result of the projected global changes. The fact that precipitation changes are also uncertain even at the global scale increases the uncertainty associated with defining likely impacts. Palaeo-based reconstructions do not provide further refinement as the uncertainty associated with derived temperature and precipitation changes are at least as large as those associated with computer-generated scenarios.

Contributing to the uncertainty in the responses of seasonal snow cover, ice and permafrost is the relative limited understanding of their sensitivities and behaviour in relationship to climate and climatic changes. Furthermore, other influential factors such as vegetation and human activity are also sensitive to climatic changes. Therefore, a better understanding of the response of seasonal snow cover, ice and permafrost to climatic changes requires a comprehensive modelling approach.

Socioeconomic consequences of these impacts will be significant for those regions which depend on snow and ice for water resources, and their social and economic welfare (eg recreation and tourist industry). Proposed implications of permafrost degradation will adversely affect structures and facilities which have been designed assuming continuation of current permafrost conditions for their structural support and integrity. Response strategies to adapt to these changes which could include abandonment have both social and economic costs associated with them. Implications of changes in seasonal snow cover, ice and permafrost for ecosystem health and structure, and terrain characteristics could also be significant.

Understanding the socioeconomic consequences of proposed impacts on seasonal snow cover, ice and permafrost is in its infancy. In most cases the studies have not included a comprehensive approach and have not integrated appropriate representatives of sociological and economics communities. Continuing to limit the scope of these types of studies will limit our understanding of the full range of socioeconomic consequences.

Of particular importance in defining socioeconomic consequences is understanding how projected changes in seasonal snow cover, ice and permafrost could affect existing structures and how they could be modified to allow them to adapt to the proposed changes. In some cases, existing structures and facilities may have to be dismantled and new ones constructed whereas in others various degrees of retrofitting could be necessary. Retrofitting costs will need to be assessed and taken into consideration in construction costs for those structures and facilities that could experience a change during their lifetime. New design and construction standards that consider the proposed impacts of climatic changes and associated risks will need to be developed for structures and facilities that rely on, or are affected by, seasonal snow cover, ice and permafrost (eg hydroelectric dams, pipelines, urban infrastructure etc).

Seasonal snow cover, ice and permafrost are ideally suited for early detection of the effects on climatic changes. Despite the complicated nature of their responses, monitoring their behaviour could provide an effective indicator of climatic changes.

Increasing our understanding of the dynamics of seasonal snow cover, ice and permafrost, the factors that control them and the impacts of climatic changes and associated socioeconomic consequences are of upmost importance. Activities that should be undertaken to promote this include:

- Accurate projections of climatic changes, including seasonal effects, are required on a regional level. These are needed to assess the timing, duration, severity of climatic changes and the associated risks.

- Establishment or enhancement of integrated, systematic observation programs at the regional and local level and with cooperation internationally. These observation programs should be as comprehensive as possible and include coincident climatic and other (eg biological, pedological, geological etc) observations as required. Commensurate with these programs, is the need to promote research on the use of more efficient ground-based systems and remote sensing technologies (eg satellite measurements, laser altimetry, seismic technologies and ground-probing radar) and the interpretation of the data.

- In the case of permafrost, ground temperatures throughout the permafrost layer over long time periods and that are spatially representative are required to provide information on regional variations in permafrost responses to warming climate. An international network of deep (minimum of 100-200 m but preferably 1-2 km) boreholes on north-south transects should be established. The occurrence and distribution of gas hydrates found in and beneath permafrost need to be assessed to ascertain potential methane releases.

- A globally representative network of glacial and associated climatic observations for glaciers should be established and maintained. Mountain glaciers are among the clearest and most easily recognisable indicators of changes in climate (a direct link to summer temperatures). They 'record' both yearly variations and long-term changes and are relatively undisturbed by the direct action of humans. Mass balance studies are being carried out in different climatic zones and representative regions, however, significant gaps in the observation network exist mainly in the Southern Hemisphere and in the developing countries.

- Sensitive structures on permafrost such as pipelines, tailings dams, water retaining dykes and toxic waste sites should be monitored to check on the influences of climatic changes on their integrity. This information would assist in defining the risk of damage or catastrophic collapse of associated structures and, thus the need and type of remedial action necessary.

- The areal distribution of seasonal snow cover, ice and permafrost need to mapped on meaningful temporal and spatial scales to permit comparisons of changes in distribution under various climatic change scenarios. This should be done at both regional and global scales to allow broad application of the produced maps. In the case of permafrost, mapping criteria and internationally agreed

operational definitions need to be established. In alpine basins the total volume of water stored in the seasonal snow pack is not monitored but, rather, measurement of snow depth and density at index points is relied on. It is not obvious that these will remain representative with climatic warming, and better methods of monitoring the spatial distribution of seasonal snow cover need to be developed.

- **Regional and local analyses of the impacts of projected changes in climate on seasonal snow cover, ice and permafrost are required. These studies should be comprehensive including globally representativeness, direct and secondary impacts, feedback mechanisms, risk analyses, and associated socioeconomic consequences. These requirements can best be met through multidisciplinary impacts programs which include representatives from groups typically involved in impact studies along with botanists, economists, foresters, sociologists, zoologists etc. To mount these impact programs, national and international research funding agencies should be encouraged to support multidisciplinary impact studies. International coordination of these impact studies is essential and could be encouraged through co-operation between existing national and international agencies and associations.**

- **Dynamic models of the behaviour of seasonal snow cover, ice and permafrost which can address the implications of climatic changes should be developed and refined, especially those capable of operating at regional scales. To produce such models the relationships between the temperature of the air, precipitation, cloud cover and the behaviour of seasonal snow cover, ice and permafrost need to be more precisely defined. The role of other factors such as terrain, vegetation cover, human disturbances and, in the case of permafrost, the surface organic layer require particular attention.**

- **Research on appropriate design and construction standards for structures and facilities in areas which will experience changes in seasonal snow cover, ice and permafrost should be conducted. This includes defining standards for retrofitting and for new structures and facilities. This type of research could be undertaken by both private and public agencies and should be supported by appropriate funding agencies.**

- **The projected changes in the seasonal snow cover, ice and permafrost due to climatic changes should not be cause for neither alarm nor complacency. Those charged with planning and design responsibilities should be made aware of and sensitised to the probabilities of and quantitative uncertainties related to issues of climatic changes and proposed effects on seasonal snow cover, ice and permafrost. This necessitates the development and dissemination of appropriate education and information materials. Research results including impacts studies should also be made more readily available. Existing national and international agencies and associations should be encouraged to undertake this vital task.**

Figure 7.1 Global distribution of permafrost

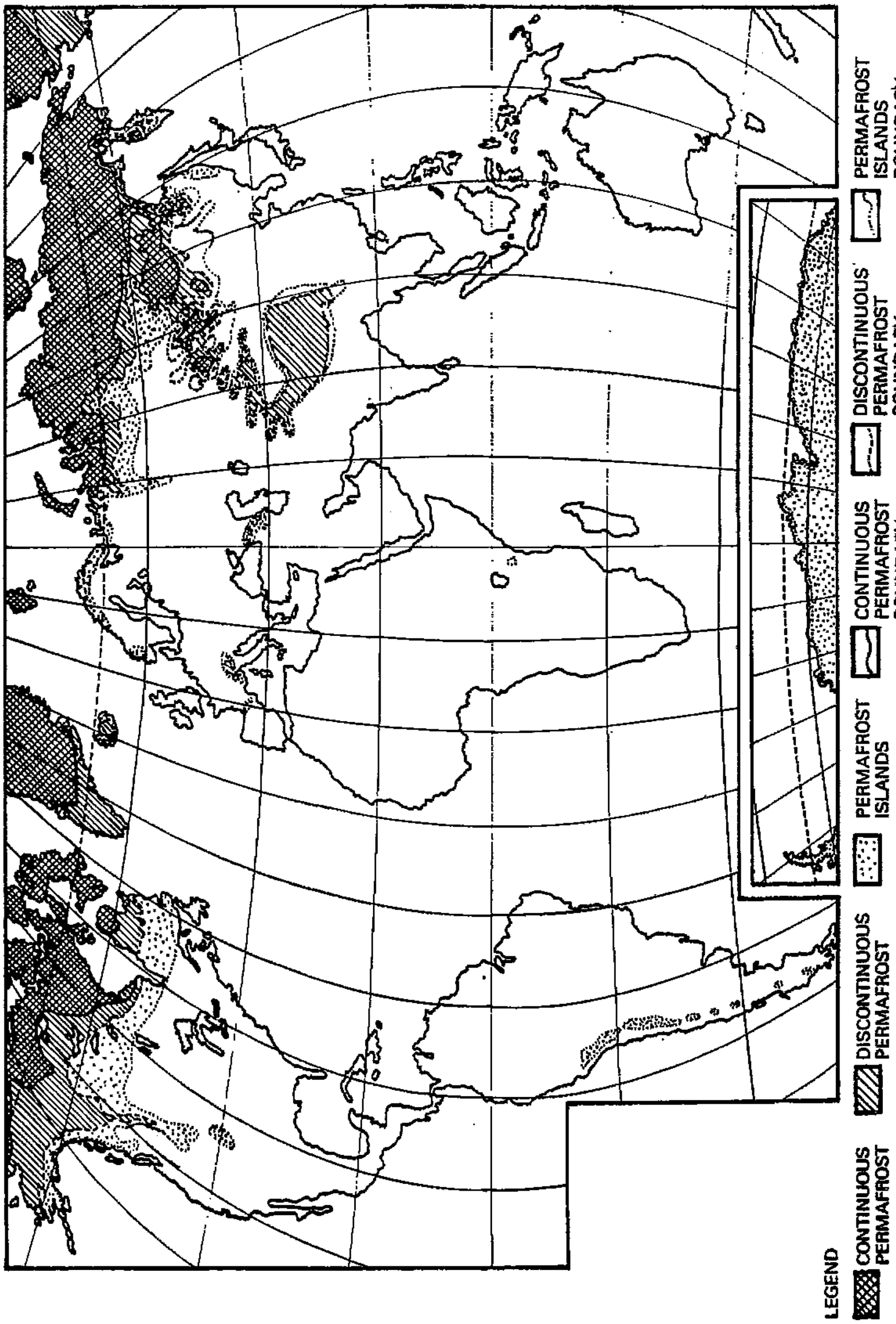


Figure 7.2 Schematic representation of the interrelations in the atmosphere -'buffer layer'- permafrost system (Nieuwenhuijzen and Koster, 1989)

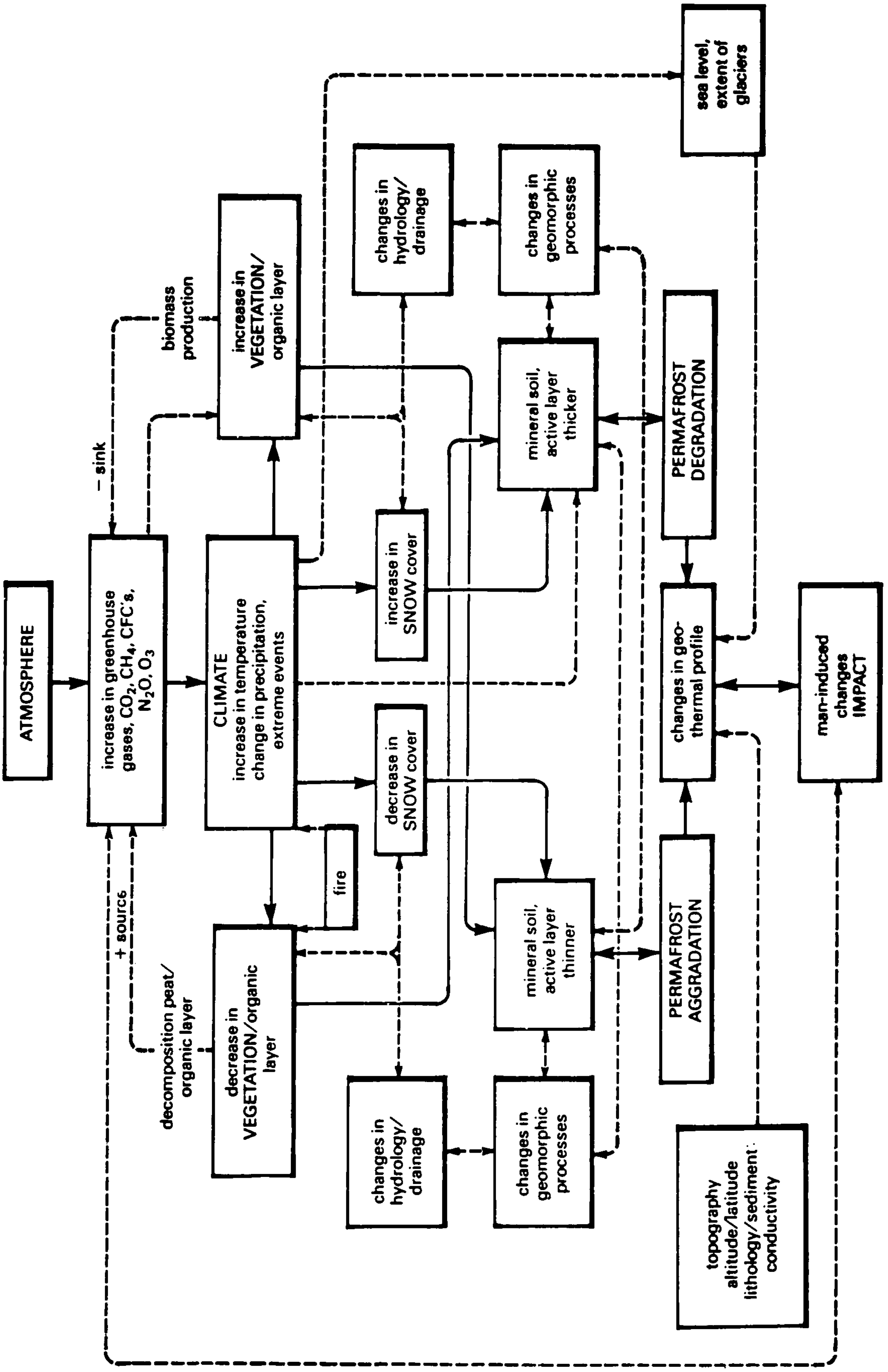


Figure 7.3 **Projected changes in the distribution of continuous permafrost in the USSR as a result of a 2°C increase in mean annual global temperature**

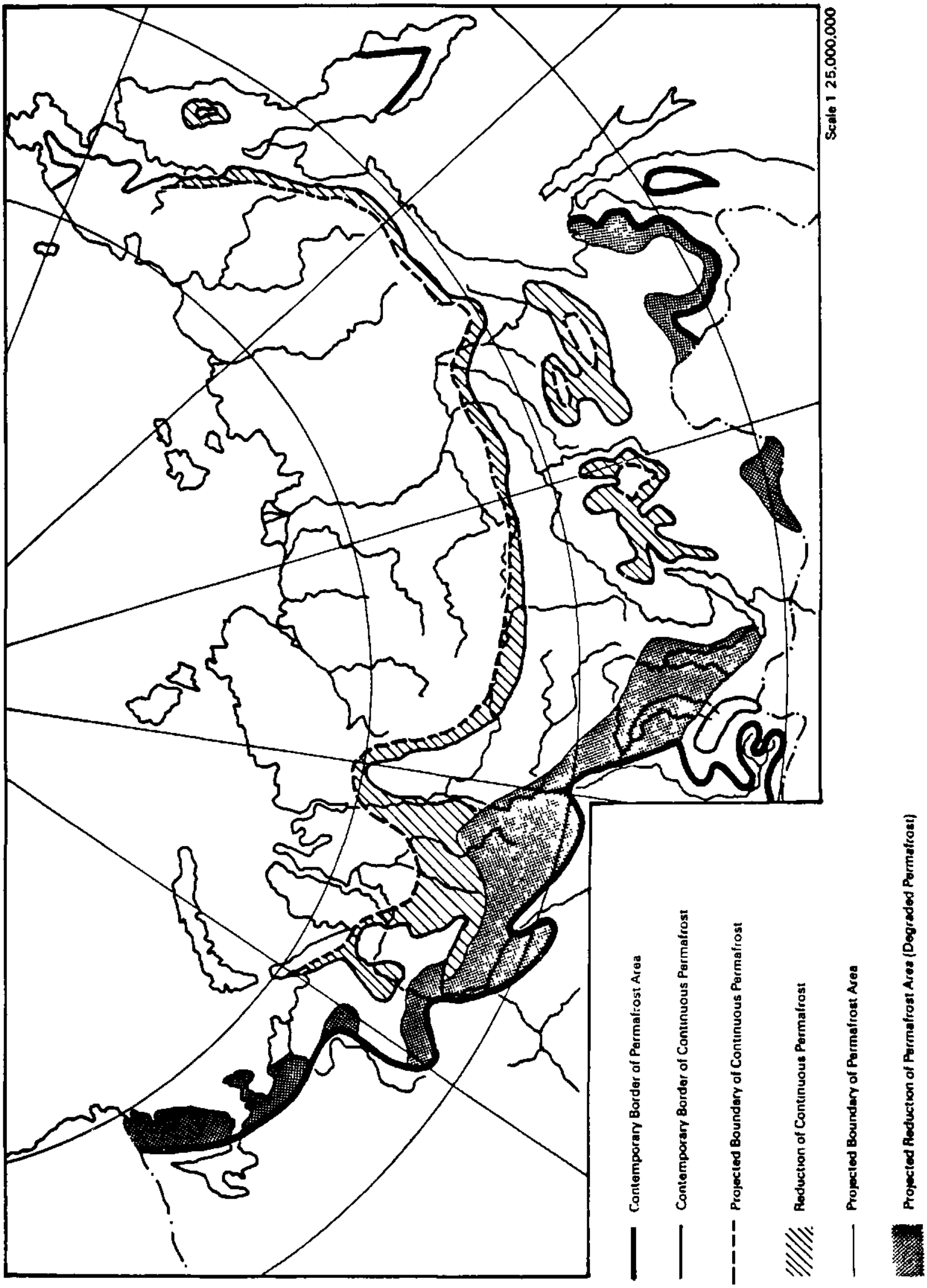


Figure 7.4a Projected changes of permafrost in the USSR along a N-S transect at approximately 83-85° E longitude (Velichko et al., 1990)

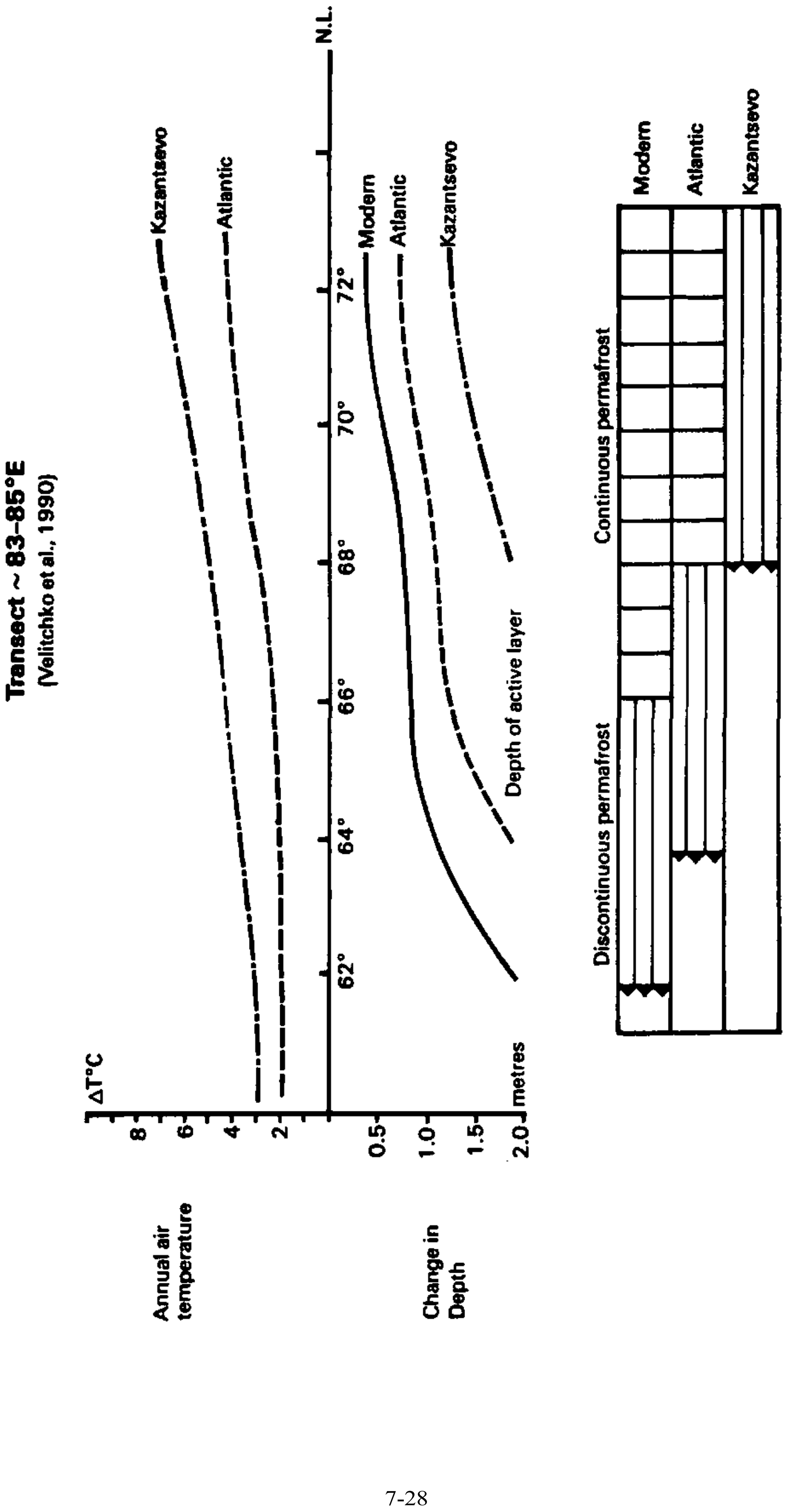
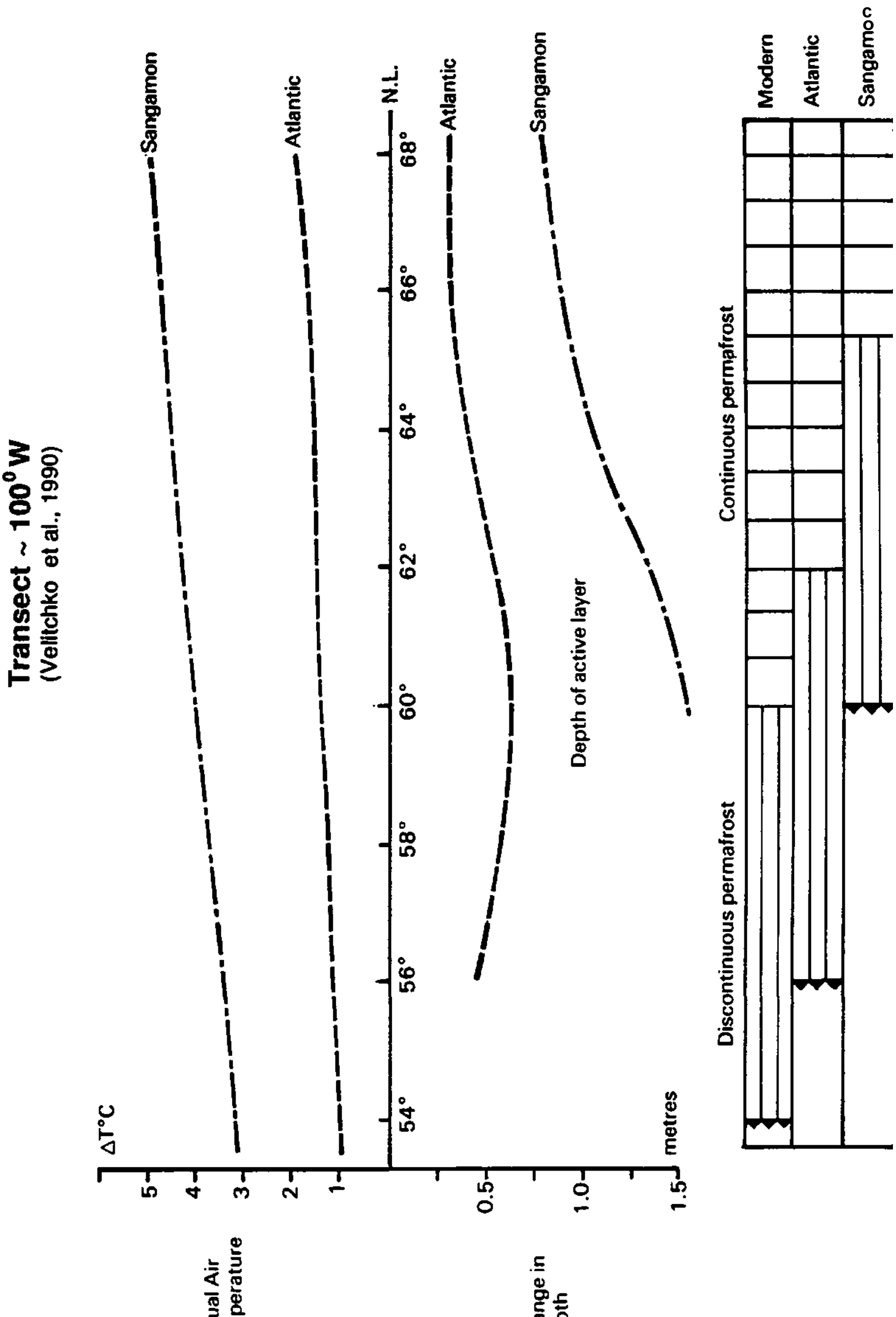


Figure 7.4b Projected changes of permafrost in Canada along a N-S transect at approximately 100° W longitude (Velichko et al., 1990)



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